TRAINING COURSE SERIES No. 9

Non-destructive Testing: A Guidebook for Industrial Management and Quality Control Personnel

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1999

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FOREWORD

The introduction and application of non-destructive testing (NDT) in industry is grossly misrepresented and misunderstood. It is often said that introduction of this expensive technology does not give any tangible returns or at least does not give returns proportional to the investment made. The facts, however, are exactly opposite to this notion and thinking. In fact, NDT, when appropriately applied, gives tremendous returns by way of savings in scrap by lowering the ultimate rates of rejection, saving valuable manufacturing time, increasing the overall quality and reliability of manufactured goods, providing an extension of plant life through preventive maintenance, saving unnecessary shutdowns, particularly through in-service inspection, and enhancement of a particular industry's reputation and consequent increased sales and profits. Therefore, even from a purely commercial viewpoint, NDT is of utmost importance for an industrial concern. The additional considerations of NDT's role in safety, failure and consequent accident prevention leave no doubt at all about the value and need of NDT.

It is this point that needs to be fully appreciated by the industrial managers and decision makers at all levels. Management ought to understand in quite an unambiguous way that their products can only survive in the highly competitive markets of today if they have the adequate and optimum quality. This quality can be built into the manufactured goods only if suitable measures and methods of quality control are employed and that the most suitable methods in most situations are the non-destructive testing methods.

Experience shows that in many cases of industrial decision making, proper knowledge of various aspects of a particular technology plays an important role. Therefore, if positive decisions are desired to be taken in favour of introducing NDT in industry in any country, its decision makers should be properly equipped with knowledge and information about this area of technology. It was with this thinking and background that training courses were organized, first in Pakistan, with the help of IAEA assistance. Each course was of two weeks duration and covered quite comprehensively various aspects of NDT technology. The topics selected included NDT methods, their applications, capabilities and limitations; economic and administrative aspects of NDT; codes and standards; quality assurance; education, training and certification of NDT personnel and sources of information in NDT. Various manufacturing processes and the typical defects associated with them were also reviewed. The course also included demonstration practicals on all the basic five methods of NDT and, to keep the managers interested and fully occupied, a token examination was given on the last day. These courses were very well received and appreciated by all the participants, most of whom were the middle level managers in their industries. One indicator of the success and the interest it generated was the demands from these managers for training of their staff in NDT. No doubt that two weeks proved to be too long a period for which the management personnel could afford to be away from their establishments. Nevertheless, the topics covered have been found to be quite informative and of fundamental importance for impressing upon the management personnel the importance and need for NDT. A shorter version of this can be extracted from these topics and given in the form of executive management seminars. It has therefore been considered appropriate to compile the lectures delivered at these courses in the form of a book such as to make it suitable for use in the other countries of the region, as well as other regions of the world.

The IAEA expert for these training courses held in Pakistan was J. Zirnhelt of Canada and the contents of some of the sections are based on his lectures and are duly acknowledged. Some

portions of the book have been directly adopted from the Training Course Series No. 3 entitled Industrial Radiography: Manual for the Syllabi Contained in IAEA-TECDOC-628, "Training Guidelines in Non-destructive Testing Techniques" (IAEA, 1992). The remaining sections were developed by A.A. Khan and his colleagues at the National Centre for NDT (NCNDT) of the Pakistan Atomic Energy Commission. Different sections of the book were then sent to the national co-ordinators of the NDT sub-project of RCA in the region of Asia and the Pacific for their comments and suggestions. The draft was then finalized by incorporating the recommended changes. During the process of compilation of the training notes guidance and support were provided by a large number of persons, especially from the NCNDT, the OAEP, Thailand and the RCA Co-ordinator's office at the IAEA. The IAEA wishes to express its appreciation to all those who have contributed to the production of these training course notes and to the governments and organizations whose financial and technical support made this publication possible.

EDITORIAL NOTE

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1. THE IMPORTANCE OF NON-DESTRUCTIVE TESTING

1.1 THE SCOPE OF NDT

1.1.1 Need and definition of NDT

An industrial product is designed to perform a certain function. The user buys it with every expectation that it will perform the assigned function well and give a trouble-free service for a reasonable period of time. The level of guarantee or certainty with which a trouble-free service can be provided by any product may be termed as its degree of reliability. The reliability of a machine or an assembly having a number of components depends upon the reliability factors of all the individual components. Most of the machines and systems in the modern day world, for example, railways, automobiles, aircraft, ships, power plants, chemical and other industrial plants, etc., are quite complex having thousands of components on which their operation and smooth running depends. To ensure the reliability of such machines it is important that each individual component is reliable and performs its function satisfactorily.

Reliability comes through improving the quality or quality level of the components or products. A good quality product can therefore be termed as one which performs its assigned function for a reasonable length of time. On the other hand products which fail to meet this criterion and their failure or breakdown occurs unpredictably and earlier than a specified time may be termed as bad or poor quality products. Both these types of products differ in reliability factors or quality levels.

The quality of products, components or parts depends upon many factors important among which are the design, material characteristics and materials manufacturing and fabrication techniques. Quality may be defined in terms of defects and imperfections present in the materials used for making the product or the presence of such defects and imperfections in the finished product itself. Many defects can also be formed in products during service. The nature of these defects differs according to the process of its design and fabrication as well as the service conditions under which it has to work. A knowledge of these defects with a view to determining them and then minimizing them in a product is essential to achieve a better or an acceptable level of quality.

An improvement in the product quality to bring it to a reasonable quality level is important in many ways. It increases, as already mentioned, the reliability of the products and the safety of the machines and equipment and brings economic returns to the manufacturer by increasing his production, reducing his scrap levels, enhancing his reputation as a producer of quality goods and hence boosting his sales. There is therefore a need to have methods by which the defects in the products can be determined without affecting their serviceability.

A wide variety of test schemes exist, some destructive and some non-destructive. Strictly speaking non-destructive testing has no clearly defined boundaries. According to ASTM E-7 non-destructive testing (NDT) is the development and application of technical methods to examine material of components in ways that do not impair future usefulness and serviceability in order to detect, locate, measure

and evaluate discontinuities, and other imperfections, to assess integrity, properties and composition; and to measure geometrical and physical characteristics. The terms non-destructive testing (NDT) and non-destructive inspection (NDI) are taken to be interchangeable, but a newer term non-destructive evaluation (NDE) is coming into use. In NDT or NDI, in flaw detection applications, the end product is taken to be a description of the flaws which have been detected in terms of their nature, size, and location. From this, either in conjunction with a standard for acceptable/rejectable flaws, or a knowledge of, for example, fracture mechanics, a decision is made by the designer, but in practice may be left to the NDT personnel, or the NDT inspector. In NDE, it is assumed that this acceptance/rejection of flaws is part of the non-destructive testing process.

Non-destructive testing (NDT) plays an important role in the quality control not only of the finished products, but also of half finished products as well as the initial raw materials. NDT can be used at all stages of the production process. It can also be used during the process of establishing a new technology by product quality or when developing a new product. Outside the manufacturing field, NDT is also widely used for routine or periodic control of various items during operation to ascertain that their quality has not deteriorated with use.

1.1.2 Methods of NDT

The methods of NDT range from the simple to the complicated. Visual inspection is the simplest of all. Surface imperfections invisible to the eye may be revealed by penetrant or magnetic methods. If really serious surface defects are found, there is often little point in proceeding to the more complicated examinations of the interior by ultrasonics or radiography. The principal NDT methods are visual or optical inspection, dye-penetrant testing, magnetic particle testing, eddy current testing, radiographic testing and ultrasonic testing. The basic principles, typical applications, advantages and limitations of these methods are briefly described in Section 3. Given in Section 3 are also a number of other NDT methods that exist. These are used only for specialized applications and consequently are limited in use. some of these methods are neutron radiography, acoustic emission, thermal and infra-red testing, strain sensing, microwave techniques, leak testing, holography, radioisotope gauges and analytical methods.

In general the various NDT techniques can be placed into two categories: active and passive. The active techniques are those where a test medium is applied to the test specimen and a response is expected if a flaw is present. This response is then detected by some means and recorded. Magnetic particle testing, ultrasonic testing and radiography fall into this category. Passive techniques, on the other hand, are those that monitor or observe the item in question during either a typical load environment or a proof cycle and attempt to determine the presence of a defect through some reaction of the specimen. Acoustic emission, noise analysis, leak testing, visual examination, and some residual magnetic techniques are in this classification.

Non-destructive testing has become an essential part of every industrial tool box. Building industrial plants or welded structures without NDT today would be like building without measuring or cleaning or welding. Maintaining aircraft, refineries

or rotating equipment without NDT would be like maintaining without lubrication or checking for tightness or for corrosion.

1.1.3 Relationship to destructive testing

To verify the integrity of a fabricated component, it is always possible to cut or section through the components and examine the exposed surfaces. Components can be pulled or stressed and pressurized until failure to determine their properties of strength and toughness. Welds can be bent to determine the presence of cracks. Materials can be chemically treated to determine their composition. These are some forms of destructive testing. Unfortunately this approach of destructive testing renders the component useless for its intended use as against non-destructive testing which can be performed on the components and machines without, in any way, affecting their service performance. A comparison of destructive and non-destructive testing methods is given in Table 1.1

1.2 THE APPLICATIONS OF NDT

1.2.1 Applications in design

The beneficial effects of non-destructive evaluation can be felt in engineering design. For example, in mechanical design, a factor-of-safety, typically defined as the ratio of design stress over the expected stress, is introduced in order to allow for a variety of uncertainties. The nature and often catastrophic results of these uncertainties have been well described in the literature dealing with fracture and material failure. One of the principal uncertainties is the performance of the components used in the construction of a mechanical system. Manufacturing irregularities, such as voids, inclusions, unfavourable patterns, and hardness affect the performance of the final part. It is no longer satisfactory for the engineer to simply specify that the material shall be free of defects. There must be more assurance that this is the case. The use of non-destructive evaluation in the quality control of manufactured parts can provide this assurance and thus increase the certainty that an item will perform as intended. With this, then, a lower factor-of-safety may be possible with a resulting overall saving in weight and cost of an item. This can best be done in the presence of firm knowledge that there are no flaws, as shown, for example, by 100% radiography. In practice, this is done by the writers of codes. For example, the widely used ASME code permits the full thickness of a weld to be used in calculations if the weld is radiographed 100%. In the absence of such radiographs, the designer is limited to using 80% of that thickness in his calculations.

Non-destructive evaluation can play a significant role in obtaining an efficient, long-lived design of components and operating mechanics. The combined advances of NDE and fracture mechanics in recent years have radically affected the approach to mechanical design.

Several axioms describing this new approach to design are given. Axiom 1 states "All materials contain flaws." This is in contrast to the earlier philosophy where it was felt to be sufficient for the design engineer to simply state in his specifications that the materials contain flaws. It is now the responsibility of the design engineer

to first know the fracture mechanics characteristics of the material that is being used and, second, to assure that NDE has been used to prevent the occurrence of potentially hazardous defects.

TABLE 1.1 : COMPARISON OF DESTRUCTIVE AND NON-DESTRUCTIVE TESTS.

DESTRUCTIVE TESTS	NON-DESTRUCTIVE TESTS
1. Tests usually simulate one or more service conditions. Consequently, they tend to measure serviceability directly and reliably.	1. Tests usually involve indirect measurements of properties of no direct significance in service. The correlation between these measurements and serviceability must be proved by other means.
2. Tests are usually quantitative measurements of load for failure, significant distortion or damage, or life to failure under given loading and environmental conditions. Consequently they may yield numerical data useful for design purposes or for establishing standards or specifications.	2. Tests are usually qualitative and rarely quantitative. They do not usually measure load for failure or life to failure, even indirectly. They may, however, reveal damage or expose the mechanisms of failure.
3. The correlation between most destructive test measurements and the material properties being measured (particularly under simulated service loading) is usually direct. Hence most observers may agree upon the results of the test and their significance with respect to the serviceability of the material or part.	3. Skilled judgement and test or service experience are usually required to interpret test indications. Where the essential correlation has not been proven, or where experience is limited, observers may disagree in evaluating the significance of test indications.
4. Tests are not made on the objects actually used in service. Consequently the correlation or similarity between the objects tested and those used in service must be proven by other means.	4. Tests are made directly upon the objects to be used in service. Consequently there is no doubt that the tests were made on representative test objects.
5. Tests can be made on only a fraction of the production lot to be used in service. They may have little value when the properties vary unpredictably from unit to unit.	5. Tests can be made on every unit to be used in service, if economically justified. Consequently they may be used even when great differences from unit to unit occur in production lots.
6. Tests often cannot be made on complete production parts. The tests are often limited to test bars cut from production parts or from special material specimens processed to simulate the properties of the parts to be used in service.	6. Tests may be made on the entire production part or in all critical regions of it. Consequently the evaluation applies to the part as a whole. Many critical sections of the part may be examined simultaneously or sequentially as convenient and expedient.

TABLE 1.1. (cont.)

DESTRUCTIVE TESTS	NON-DESTRUCTIVE TESTS
7.A single destructive test may measure only one or a few of the properties that may be critical under service conditions.	7. Many non-destructive tests, each sensitive to different properties or regions of the material or part, may be applied simultaneously or in sequence. In this way it is feasible to measure as many different properties correlated with service performance as desired.
8. Destructive tests are not usually convenient to apply to parts in service. Generally, service must be interrupted and the part permanently removed from service.	8. Non-destructive tests may often be applied to in service parts or assemblies without interruption of service beyond normal maintenance or idle periods. They involve no loss of serviceable parts.
9. Cumulative change over a period of time cannot readily be measured on a single unit. If several units from the same lot or service are tested in succession over a period of time, it must be proven that the units were initially similar. If the units are used in service and removed after various periods of time, it must be proven that each was subject to similar conditions of service, before valid data can be obtained.	9. Non-destructive tests permit repeated checks of a given unit over a period of time. In this way, the rate of service damage, if detectable, and its correlation with service failure may be established clearly.
10. With parts of very high material or fabrication costs, the costs of replacing the parts destroyed may be prohibitive. It may not be feasible to make an adequate number and variety of destructive tests.	10. Acceptable parts of very high material or fabrication costs are not lost in non-destructive testing. Repeated testing during production or service is feasible when economically and practically justified.
11. Many destructive tests require extensive machining or other preparation of the test specimens. Often, massive precision-testing machines are required. In consequence the cost of destructive testing may be very high, and the number of samples that can be prepared and tested may make severe demands upon the time of highly skilled workers.	11. Little or no specimen preparation is required for many forms of non-destructive tests. Several forms of non-destructive testing equipment are portable. Many are capable of rapid testing or sorting and in some cases may be made fully automatic. The cost of non-destructive tests is less, in most cases, both per object tested and for overall testing, than the cost of adequate destructive tests.
12. The time and man-hour requirements of many destructive tests are very high. Excessive production costs may be incurred if adequate and extensive destructive tests are used as the primary method of production quality control.	12. Most non-destructive test methods are rapid and require far fewer man-hours or actual hours than do typical destructive tests. Consequently testing all the production units cost normally less than, or comparable, to the costs of inspecting destructively only a minor percentage of the units in production lots.

The beneficial role that NDE is able to play in the initial design process may be presented through evaluation of fatigue characteristics of components. In general the parts operating at lower stress levels would be expected to have a longer fatigue life than the ones operating at higher stress levels. However, largely due to material and manufacturing variations actual practice has shown that in the vicinity of fatigue failure line there is a considerable uncertainty. In order to produce a more conservative design, the operating stress should be removed from this uncertain area. This is accomplished with the factor of safety. Changes in the operating conditions after the component is placed in service will result in a new factor of safety. For example, either an increase in the load stress or an extended life operation would result in a decrease in the factor of safety and a corresponding increase in the likelihood of failure.

The study of fracture mechanics has given the design engineer an added dimension in the creation of designs as an integrator of material properties, design stress, and flaw detectability. In fracture mechanics, a distinction is made between the initiation of a crack and its subsequent propagation. In calculating the critical stress levels, fracture mechanics assumes the presence of a crack when most likely one does not exit. Thus, the analysis begins with a conservative assumption. With the presence of a crack assumed, the propagation in metals begins from the onset of plastic flow in a very localized region at the crack tip. Once started, it is further assumed that the crack will travel until arrested by some condition in the material. Failure prevention, then, demands that the crack be detected before reaching the critical, final failure stage.

In NDT the detectability of a flaw generally increases with its size. It is also true, however, that the probability of failure generally increases with flaw size. Recognizing the catastrophic potential for a fatigue related failure, it is prudent for the designer to consider future inspections in the original concept. Where considerable effort is required to gain access to inspect a critical part, the inspection will be more costly. Moreover, inspections that are required to be conducted in places that are difficult to reach are more likely to be performed in an ineffective manner. It is therefore imperative that the original designer plans for convenient inspection for critically stressed locations.

The items in the design process which are critical to the inspectability of a part or system are briefly mentioned here. Firstly the materials selected should have favourable fracture toughness properties. Certainly the ability of a material to arrest a crack rather than allowing it to propagate suddenly to full failure is conducive to successful NDE. The importance of a material having well established NDE properties is also stated. For example, ultrasonics may have a response in some cast materials that is different from similar wrought materials because of the increased scatter at the grain boundaries of the former. Fabrication processes that may inflict flaws or other anomalies into the part should be avoided. Of particular importance in this area are tensile stresses, introduced during fabrication, which can facilitate the initiation and propagation of a crack. The configuration of the part should be such that unnecessary section changes that might inhibit inspection are minimized. Further, critical areas should be easily accessible, either for visual inspection, NDT, or both. Finally, it is recommended that the design engineer consults frequently with the NDT engineer so that an overall satisfactory design emerges.

1.2.2 Applications in manufacturing quality

Defects in materials are either present because of the faulty manufacturing processes or due to fatigue, corrosion or similar damage during service. However, it is important to have the materials of the right quality before these are accepted for being put into service. The application of NDT during manufacture is therefore very important.

The cost of manufacturing of products is enhanced ultimately by the costs of repair, rework, replacement and even a possible loss of customer as well as the costs of delay of schedules, etc. A very careful consideration has therefore to be made to the production of quality goods during manufacturing. A key item to assure the maintenance of consistent quality and productivity can be the employment of a new process involving non-destructive testing (NDT) and inspection systems to assess and feedback product quality information. In a properly designed and qualified product that has been demonstrated as producible, NDT techniques have proved to be very reliable tools to assure consistent parts, materials, processes, and workmanship, as well as product quality.

NDT methods offer not only the advantages of discovering potential or real problems early in the production programme but also a definite feedback as to how to correct the problem at the earliest possible point.

Subcontractors can make good use of NDT capabilities. As an electronic product is built up from its piece parts to modules to printed wire boards to black boxes and eventually to the system assembly, the cost of any anomalous performance that can result in additional tests, troubleshooting, removal, rework, repair, and as a worst case the scrap increases at an exponential rate. We must therefore discover and correct any quality problems at the lowest level of assembly and as early in the product production phase as possible. To this end, NDT methods can provide a very positive approach. It is not the answer to every problem but surely should be considered. NDT methods offer a helping hand for making this a reality at all times. Consistent high quality goes hand in hand with increased productivity.

The NDT methods that are suitable for application during manufacturing are those which can detect the desired levels of defects at speeds compatible with the particular production rates. In certain pipe, tube and plate manufacturing, for example, two to three joints or lengths must be inspected every minute to keep up with production. In some other cases where a number of tests have to be performed on the same product, the inspection time may be much longer. The producer is faced with the situation that he must inspect his products at relatively high speeds and at the same time meet the quality levels verified through deliberate and comprehensive customer inspections. This, though expensive, is no more an impossible task. Considerable research and development, engineering and manpower have been expended world-wide to develop NDT systems to meet the needs and specifications of particular customer, plants and production methods. Research and development were dedicated to devising automatic systems that could operate at speeds compatible with production rates and could detect and mark deviations from acceptable product quality with a high degree of accuracy. This work has resulted in NDT systems that are fast, accurate and give reproducible

results. Automated inspection is now available for almost all the NDT methods but for regularly shaped products, such as pipes and plates, etc., ultrasonic and eddy current methods are generally employed. These have, relative to other NDT methods, much greater speeds of inspection. But such modern systems, of course, are quite expensive and therefore quite a number of manufacturers prefer to get NDT done by third parties to the satisfaction of the customer.

Many producers have adhered to the practice of using NDT solely to satisfy customer and industry requirements for finished products acceptance. These tests may be conducted at the producer's plant, at downriver marshalling yards or warehouse, or at the customer's facility. This practice provides a high degree of quality assurance, but there is little or no opportunity to apply timely corrective measures for quality-control purposes. Consequently, NDT is used only for finished product inspection, whereas a significant portion of its cost-saving can be realized only from using in-process NDT in addition to the final inspection. Some of these savings are evident. If the product that is flawed or out of tolerance because of dimensions or mechanical properties is identified early in production, it can be diverted or scrapped, thus avoiding further processing and related costs. This information alerts production planning to the fact that a certain number of make-up pieces must be processed and that there are a number of downgraded pieces available for other markets. Through early detection and repair of imperfections, the quality level of the products going into final inspection is improved. This results in a significant reduction in final inspection rejections, increased yield, and fewer miscalls by the NDT system. In-process NDT can also avoid damage to equipment which may make use of the manufactured components. The direct cost savings are evident, and additional saving through reduced handling, shipping, manpower, and claims can be surmised.

NDT techniques have advanced to the point that when properly applied, they can read mechanical and physical product parameters predictably and repeatedly. A programme that combines in-process and final NDT in a comprehensive manner might be called a non-destructive quality-control (NDQC) programme. The NDQC programme would use the appropriate NDT methods at various stages of the product manufacturing process to monitor such parameters as steel grade, dimensions, physical properties, and the nature, distribution, and occurrence rate of imperfections for feedback and feed-forward purposes. The numerous devices that are being developed for this purpose include photodiode arrays, matrix array TV cameras, lasers, infra-red devices, electromagnetic-acoustic transducers (EMATs), computer-aided tomography (CAT). The products being manufactured, say a pipe for example, could be monitored at speeds of up to 1.5 metres per second. Therefore it can be said that conscientious application of NDQC will reduce scrap losses and increase total yield by applying corrective measures before large amounts of out-of-tolerance components are produced. In short NDT can help to "make it right the first time" which is the fundamental concept of quality assurance.

1.2.3 Applications for in-service inspection

For most industrial plants the objective of its ownership is profitable and safe operation throughout its life. The required life of the plant will relate to the period of time for which its product is going to be in market demand and also the time that

the particular process used will continue to be the most economical for the production rate required. For most industrial plants, these times will be considerably in excess of the average life time of many of the plant components. An essential aspect of the plant specification and design is, therefore, to determine which of the critical components are the most likely to fail and then to ensure that these have easy maintenance access for repair or replacement. Economic assessments also need to be made to compare the relative costs, for critical components, of installing parallel stand by units to take over when one unit fails, or whether to accept the production losses that will occur when, as an alternative, the whole plant has to be stopped for repair.

The best strategy of maintenance seems to be to undertake in-service inspection of the critical components at regular intervals without having to shut down or stop the plant or the process. Non-destructive testing methods are most suited to do this job. All the machines in a plant which contain components with a performance that is critical to continued operation, and which are likely to fail at some random time, and for which the failure mode is gradual and progressive rather than sudden need to be regularly monitored. NDE can often detect fatigue cracks in the early stage before catastrophic failure occurs. The related field of fracture mechanics has placed more responsibility on those in non-destructive evaluation. When the fracture mechanics specialist states that a component possibly valued at several million dollars can remain in service provided that there are no defects present greater than a certain length, the non-destructive evaluation specialist must know the capabilities of his system to detect defects of that critical length. Thus, NDE is a valued contributor to the safe and economical performance of equipment and structures. Some typical examples of application of NDT methods for in-service inspection are the wall thickness measurements and corrosion monitoring of all sorts of pipelines and storage vessels using ultrasonic testing, monitoring the pressure vessels and other highly stressed components with the help of strain gauges and acoustic emission for any probable occurrence of stress and fatigue cracks, inspection of welds in pressure vessels using ultrasonic testing and eddy current and ultrasonic testing of critical parts in aircraft. In aircraft engines it is required to carry out routine boroscopy and radiography. Aircraft primary structure, such as frames, stringers, and fittings, are routinely inspected visually and with radiographic, eddy current, or ultrasonic testing. On the Boeing L-1011, routine inspection of the wing rear span for fatigue cracks uses both ultrasonic and eddy current testing.

Non-destructive testing can also be beneficial in reducing the frequency of unscheduled maintenance, which usually is more expensive than regularly scheduled maintenance. Often, NDT can be used to inspect questionable parts in-place on the equipment, thereby preventing an unscheduled and unnecessary shutdown if the part is in fact defect free. With assurance that there is no defect present, the equipment may continue operating without fear of failure.

Additionally, scheduled maintenance periods may be lengthened with the proper use of NDT in the maintenance cycle. Knowing from an inspection that crucial parts are not approaching failure may allow the machine to operate safely for a

longer period of time. Less frequent maintenance may be cost-effective provided that the cost of operation is not increased due to an unexpected failure.
Considerable dedication is required in order to establish a non-destructive testing programme that will yield sufficient confidence as to where a factor of safety or maintenance cycle can be changed. To do that requires positive communication and thorough understanding of the technical principles involved. One "missed defect" can cause a failure that can erase the saving accrued from years of expensive testing.

1.2.4 Applications in plant life extension

The plant life extension can be defined as "the systematic evaluation of important plant systems and components to identify means to detect, monitor and trend, prevent and mitigate the effects of age-related degradation through changes in hardware, operation, maintenance and surveillance to ensure safe and economic operation during the life extension period in order to provide technical justification for licence manual". A fracture mechanics approach is widely used to project remaining life. This approach is based on assumptions about the absence of flaws. NDT can help in establishing the confidence level of these assumptions by finding that there are really no flaws present or, if present, what are their types, sizes and locations in the tested components. In the presence of this information the fracture mechanics analyst can decide how far can a particular component still be used. Using NDT therefore for frequent monitoring of the equipment for a suitable period could produce indications of whether or not the operating conditions had been placed too near the failure line. There may be sufficient economic justification for increasing the load or extending the life, provided that it can be done without catastrophic consequences.

The reliability of data generated by NDT is important in plant life extension studies. Credibility lost by different results under identical conditions on the same component is difficult to regain. NDT practitioners are being challenged to increase the level of precision of equipment and technique to meet the requirement of plant life extension, not only in the nuclear power industry, but also in other industrial sectors.

1.2.5 Other applications

Although a great deal of non-destructive testing is carried out for flaw detection in materials, e.g. the detection of weld defects, lack of bond in adhesive joints, and fatigue cracks developing during service, it should not be forgotten that NDT also has important applications in the examination of assemblies, to detect misassembled components, missing or displaced parts, to measure spacings, etc. In many of these applications, it is possible to be quite specific on what it is necessary to detect i.e. the required flaw sensitivity, or what accuracy of measurement is needed, and devise an NDT technique suitable for the particular application which may often be much faster or cheaper than a more conventional technique. Examples of this type are ordnance inspection (fuses, etc.) for correction of assembly, aero

jet-engine inspection during test running to measure blade spacings during speed changes, ultrasonic thickness gauging, and metal alloy sorting.

1.3 THE IMPACT OF NDT IN DISASTER PREVENTION

Failure due to defects originating in construction or service, no matter how minor, may have far-reaching and serious consequences. The ability of properly applied NDT methods to detect these defects makes them invaluable tools for the possible prevention of fracture through timely detection. Unexpected failure of engined components, vessels or structures can result in inestimable costs through loss of life or permanent environmental damage, and is more easily calculated by costs incurred through loss of product, plant down time and resulting repairs.

1.3.1 Loss of life

In early 1989, there were press reports of an accident in the Soviet Union in which two passenger trains were engulfed in the flames from an explosion linked to leakage from a gas pipeline with loss of life in the hundreds. Subsequent statements attributed the disaster to poor control of workmanship during construction of the pipeline. While all of the details have not been released, one is led to conclude that poor workmanship means poor welding, and poor control means poor inspection. Proper use of NDT might have prevented this disaster.

A utility company using truck-mounted aerial man lifts lost an employee when the centre post (the post about which the entire mechanism rotates) fractured at the base. The progressive fatigue could have easily been detected by NDT. Now, an annual inspection instigated as a result of this accident finds such cracks in an early stage allowing timely replacement and a safer workplace.

1.3.2 Environmental damage

Increased awareness and concern for contamination of the plants, its water ways and its atmosphere have resulted in stringent regulatory controls for the manufacturing and installation of such projects as storage tanks, pipelines, railway track, cars, ships, offshore petroleum production installations, nuclear power plants and chemical plants. In any of these, the failure of a simple valve or a seamweld could release large amounts of a damaging material onto the ground, into the air or into the water table. Dispersion is often so rapid that containment is impossible, and the results, even if not immediately toxic (like Bhopal or Chernobyl), can be irreversible. NDT methods have a significant role to play in ensuring that flaws which could result in such a failure are eliminated before installation.

1.3.3 Loss of product

In comparison to the cost of living with environmental damage or even dealing with clean up attempts, the value of the product lost through a component failure may be relatively small. The value of tanker full of crude oil or a few thousand litres of

leaked heavy water from a nuclear reactor coolant system would far exceed the cost of the NDT inspection that would have located the defect that caused it.

1.3.4 Lost time

Every operating plant has a figure for the cost of lost production due to unscheduled down time; preventive maintenance relies upon scheduled shutdowns during which all repairs, inspections and replacement can be carried out in an orderly manner. In a sugar refinery for example, a shaft (about 0.5 m in diameter, 5 m in length) which was the core of a device used for chopping and crushing sugar cane failed in service resulting in a three week shutdown while another was being made. Examination of the failure revealed it to be a fatigue crack in a highly stressed (and predictably critical) area, which could have been detected easily and monitored by ultrasonic testing without dismantling while a new shaft were being made. Timely detection of defects by an appropriate NDT method is a major factor in preventive maintenance, and can save many hours of downtime.

1.3.5 Repair costs

Another expense easily defined, is the cost of replacement or repair necessitated by failure which could have been prevented by timely detection of a defect by NDT. The cost to a manufacturer resulting from the release to a customer of defective components and subsequent recall and reworking will far exceed the cost of preventive inspection. Failure of a pipeline or a bridge will result in costly repairs, more costly than if carried out during original construction.

1.4 THE HISTORICAL DEVELOPMENT OF NDT

1.4.1 Factors influencing development

The history of NDT and its increasing level of acceptance is well documented and perhaps most vividly illustrated by Betz "Tree of Growth' of Non-destructive Testing" in his book on "Principles of Magnetic Particle Testing", Magnaflux Corporation, Chicago 1967. While his particular illustration stops at 1970, the two subsequent decades have been a period of continual expansion, acceptance and growth. Of particular interest in this context is consideration of the driving forces that have fuelled this expansion. In the early years, development could be tied to the shipbuilding industries. In the 1950s, the nuclear industry, seeking new inspection technologies to support parallel developments in materials and applications for power production sponsored most of the development and expansion. In the 1970s, energy technologies in general were creating new demands for new applications, new materials and new problems, in the 1980s, we have seen a maturing of the industry. While there is still a strong interest in new materials and applications and the demands these make on inspection technology, the greatest driving force is perhaps a common striving for product quality. In the 1990s, quality assurance will continue to be important but we can expect to see a trend of wider usage of NDT to assist in the assessment of the condition of existing plants, and in pursuit of the confidence needed to extend design life of operating facilities of every nature.

1.4.2 Future expectations

There are two general trends within the NDT community that are influencing development and both centre around the operator. On the one hand, instrumentation is being developed to reduce the operator's involvement as much as possible through automating functions and computerizing results. On the other side there are significant efforts to quantify or standardize the human element through training and qualification. These trends will continue. External factors are several. Perhaps most important is the introduction of computers to document results to simplify instrumentation and even to analyse and interpret test data. Second in importance is an increasing demand from users for more precision, more reliability and more speed. As users become more dependent on NDT results, to support extended component life and lower factors of safety, this pressure will increase. Finally the need for specialist technicians as well as applications specialists will grow to cope with the many opportunities being presented. There is a new factor coming into NDT, which seems likely to bring major modifications to most NDT methods. This is the use of computer techniques, using small computers. Apart from the obvious, rather trivial uses to simplify calculations, it is now possible to collect, store and process vast quantities of digital data at very high speeds. For example, in ultrasonic testing, in the signals produced by a transducer from a flaw there is a mass of data which is not used in conventional ultrasonic flaw detection. This can all be taken into a data store, and computer programmes devised to extract information such as spectral composition, rise-time, pulse length, and maximum amplitude. At the moment it is not even certain, in some applications, what are the relevant properties of the signals which are needed. In addition, the computer can be used to choose the technique parameters for a given application, to adjust the equipment accordingly, and to provide warning if there are deviations, or a change in monitoring signals.

2. MATERIALS, MANUFACTURING PROCESSES AND DEFECTS

2.1 STRUCTURE OF METALS AND ALLOYS

The properties of metals can be explained in terms of the manner in which the atoms of a metal are bonded together. In this bond, called the "metallic bond", each atom of the metal is closely surrounded by many similar atoms, each with only a few electrons in its outer electron shell. In this situation the electron clouds overlap and the loosely held outer electrons are so completely shared as to be no longer associated with individual atoms. Leaving the metal atoms in place as ions, they form an electron gas, a pervasive glue that moves freely among the ions and binds them together (Figure 2.1).

Because the electrons are free to move in an electric field, metals conduct electricity. Because free electrons absorb and then radiate back most of the light energy that falls on them, metals are opaque and lustrous. Because free electrons can transfer thermal energy, metals conduct heat effectively. The metallic bond is non-specific, which explains why different metals can be alloyed or joined one to

another. It is also non-directional, pulling equally hard in all directions. It therefore binds the metal atoms tightly, so that their cores (nuclei and inner shell electrons) fit closely among one another. The close packing favoured by the metallic bond is best realized in certain regular crystalline structures. These structures, although resistant to tension, offer less resistance to shearing forces, and thus they explain the ductility of metals. They are by definition dense, and thus they explain the comparative heaviness of metals. The mechanical properties of metals then derive from their crystalline structure, i.e. the atoms in the solid state of a metal are arranged in definite three dimensional geometric patterns to form crystals or grains of the metal. The network formed by joining the centres of the atoms in a crystal is called the 'space lattice' or 'crystal lattice' of the metal. The smallest volume in a space lattice which properly represents the position of the atoms with respect to each other is known as the unit cell. There are fourteen types of unit cells but the structures of most of the common and commercially important metals in the solid state are constructed from the following three types of unit cells:

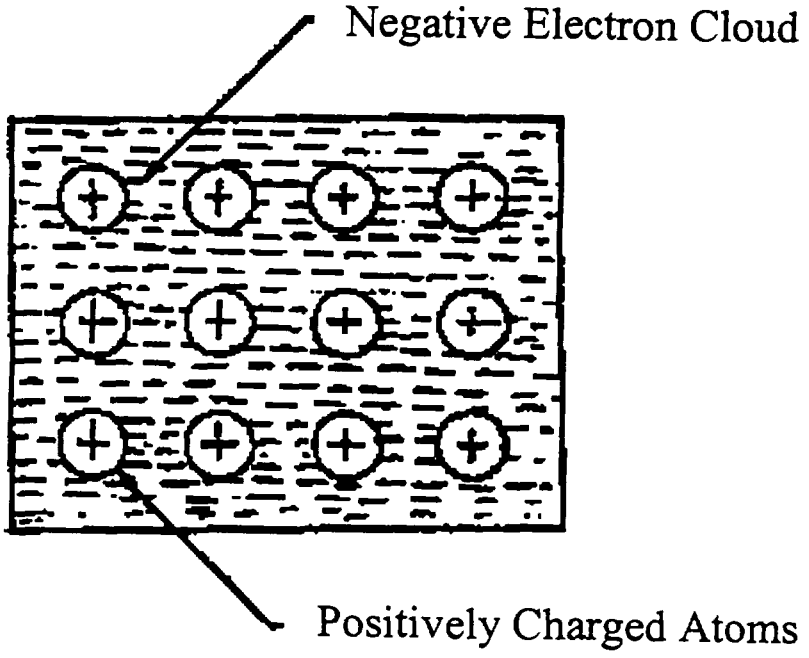

Figure 2.1 : Schematic illustration of a metallic bond.

a) Body-centred cubic

The body-centred cubic cell is made up of two atoms. Eight are located on the corners of the cube but each of them builds also a part of further seven cells meeting at that corner ($8 \times {}^{1}/_{8}$) with the ninth positioned centrally between them (Figure 2.2 (a)). The body-centred cubic is a strong structure, and in general, the metals that are hard and strong are in this form at normal temperatures. These metals include for example chromium, molybdenum, titanium, tungsten, sodium and vanadium. Steel under 723 °C also has this structure.

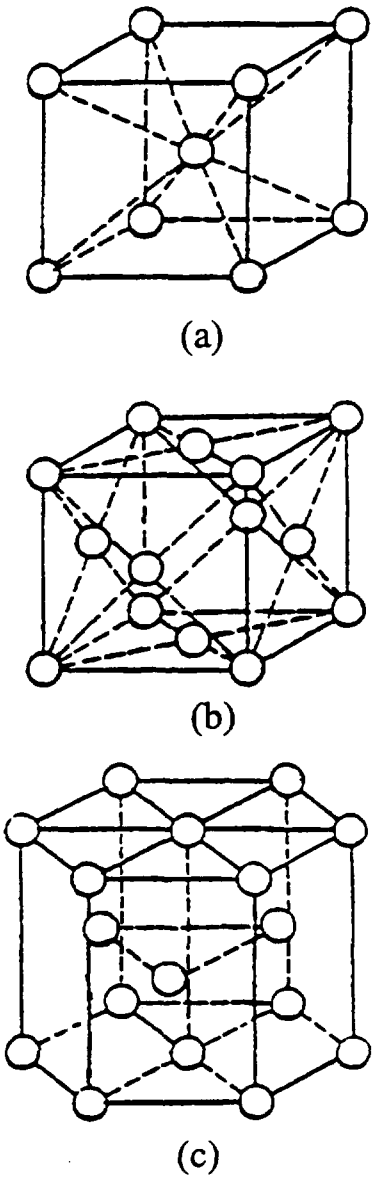

Figure 2.2 : Crystal types.

b) Face-centred cubic

Face-centred cubic cells consist of four atoms with eight at the corners ($8 \times {}^{1}/_{8}$) and the other six centred in the cube faces but each of them is also a part of the neighbouring cell ($6 \times {}^{1}/_{2}$) (Figure 2.2b). This structure is characteristic of ductile metals, which include aluminium, copper, gold, lead, nickel, platinum and silver. Iron, which is body-centred cubic at room temperature, is also of the face-centred structure in the temperature range from about 910 °C to 1,400 °C.

c) Hexagonal close-packed

Seven atoms combine to make the hexagonal close- packed unit cell. Six atoms are located in each hexagonal face at each corner ($6 \times {}^{1}/_{3}$) and one in the centre of the face ($1 \times {}^{1}/_{2}$) and there are two hexagonal faces. The three remaining atoms

take up a triangular position in the centre of the cell equidistant from the two faces (Figure 2.2 c). The metals with this structure are quite susceptible to work-hardening. Some of the more commonly used metals that crystallize with this structure are cadmium, cobalt, magnesium, titanium and zinc.

Tin is an exception to the other commonly used metals in that the atomic configuration is body-centred tetragonal, which is similar to the body-centred cubic but has wider atomic spacing and an elongated axis between two of the opposite faces (Figure 2.2a).

2.1.1 Grains (crystals) and grain boundaries

When a metal is cooled from the liquid state to the solid state, because cooling cannot be exactly the same for every atom, certain atoms will be attracted to each other to form a unit cell ahead of others. This unit cell becomes the nucleus for crystal formation. As the cooling continues other atoms will take up their positions alongside this nucleus and the crystals, or as it is usually referred to for metals, the grain, will grow in size. This orderly growth of the grain continues in all directions until it runs into interference from other grains that are forming simultaneously about other nuclei. Figure 2.3 illustrates the process of the formation of grains and grain boundaries.

Although with some metals with special treatment it is possible to grow single crystals several inches in diameter, in most metals at the usual cooling rates, great numbers of crystals are nucleated and grow at one time with different orientations.

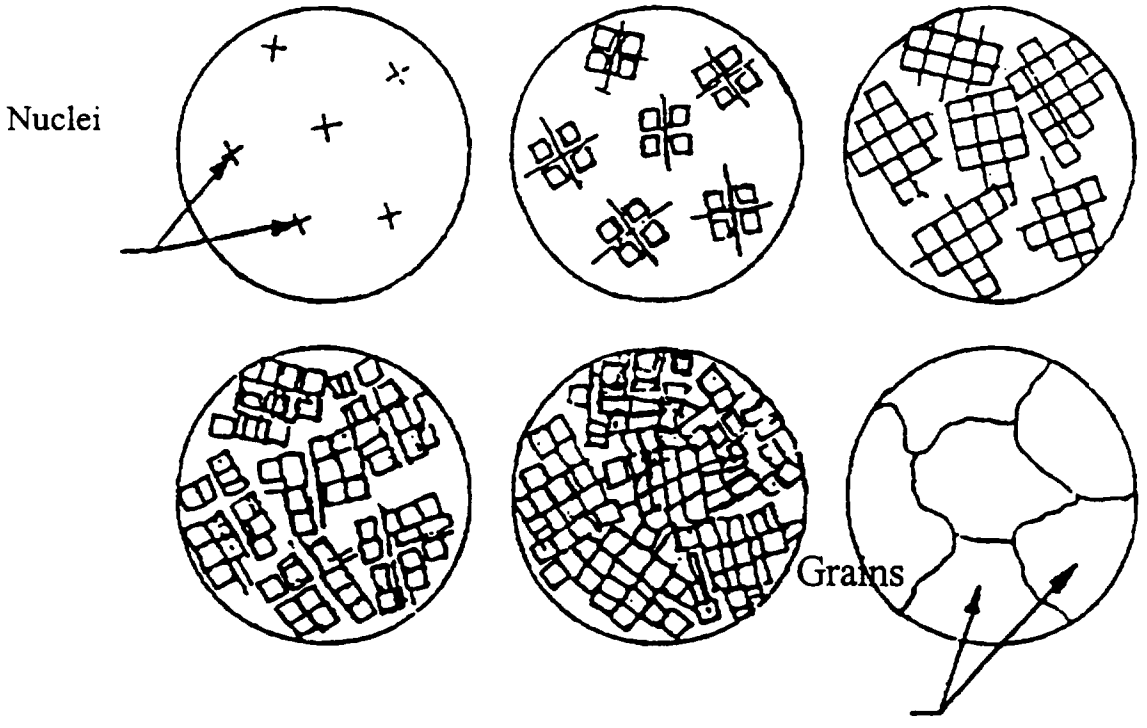

Figure 2.3 : Growth of crystals and grains during solidification.

If two grains that have the same orientation meet, they will join to form a larger grain, but if they are forming about different axes, the last atoms to solidify between the growing grains will be attracted to each and must assume compromise positions in an attempt to satisfy a double desire to join with each. These misplaced atoms are in layers about the grains and are known as grain boundaries. They are interruptions in the orderly arrangement of the space lattices and offer resistance to deformation of the metal. A fine-grained metal with large numbers of interruptions, therefore, will be harder and stronger than a coarse-grained metal of the same composition and condition.

2.1.2 Structure of alloys

Most commercially used metallic materials are not pure metals but alloys which consist of more than one element. Some of them may be non-metallic elements. Fundamentally, three modes of arrangement of atoms or phases exist in alloys. These three modes (phases) are; pure metal, solid solution and intermetallic compound. For simplicity of illustration, an alloy with two elements A and B, shall be considered in the following discussion.

a) Pure metal

There exist no B-atoms in A-crystal grains and no A- atoms in B- grains i.e. mixture of pure A-and B-crystal grains. A and B metals are mutually insoluble. This complete lack of intersolubility is theoretically almost impossible. (The solubility of one component in another may be exceedingly small but hardly zero.)

b) Solid solution

There exist B-atoms (solute) in A-crystal grains (solvent). Solid solutions are of two types: substitutional solid solutions and interstitial solid solutions.

i) Substitutional solid solution

There exist B-atoms at the lattice points of A-crystals. For example, the lattice of nickel (A-crystal) can accommodate copper atoms (B-atoms) without loosing its FCC structure (structure of A-crystal). In the Cu-Ni system the two elements can be substituted in all proportions and are said to be completely intersoluble. But commonly substitution of B-for A-atoms is limited, i.e., A and B are incompletely intersoluble.

ii) Interstitial solid solution

In the interstitial solid solution B-atoms are accommodated in the interstices gaps of the lattice of A-crystal. Light atoms with small radii such as H, N, C and B tend to take up interstitial position in alloys. The solubility of solute atoms in solvent crystals in this type of solid solution is limited. Addition of B atoms in solid solutions may cause lattice expansion or contraction and metals are

hardened (i.e. strengthened) by lattice distortion. The degree of hardening depends on the size and amount of B-atoms and the crystal structure of the A- and B- metals.

c) Intermetallic compound

Elements A and B form an intermetallic compound A B. In contrast to a solid solution, the ratio of the number of A-atoms to B- atoms is fixed (m: n), and the crystal structure is quite different from both A-and B-metal crystals and usually very complicated. Almost all the intermetallic compounds are very hard and brittle due to their complicated crystal structure.

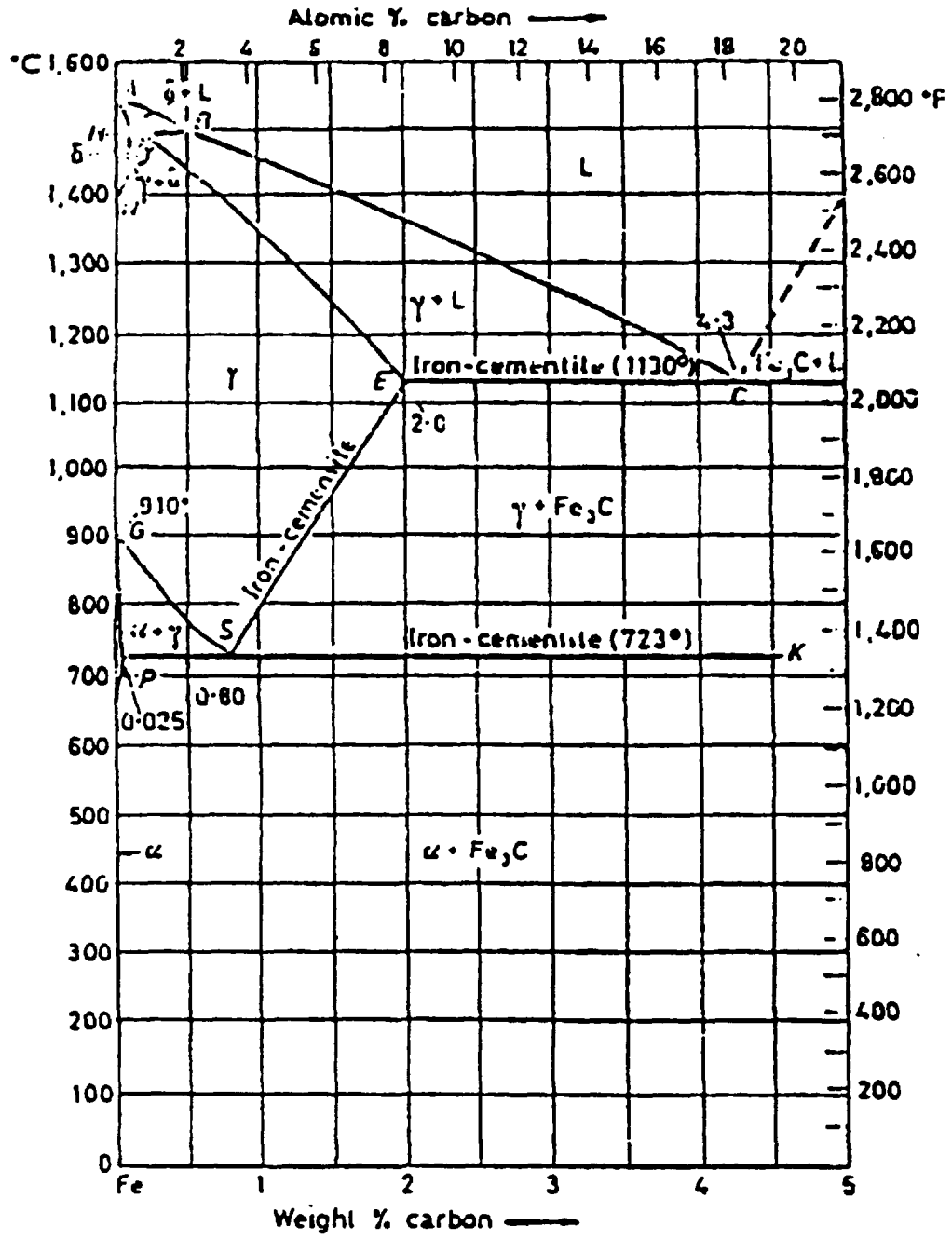

Figure 2.4 : Equilibrium diagram for iron carbon systems.

2.1.3 Allotropic transformation

Many metals exist in more than one crystal structure. The transformation when a metal changes from one crystal arrangement to another is called an "allotropic transformation" or "phase transformation". In the iron-carbon alloy system such a transformation takes place between about 1300°F to 1600°F-the exact temperature is determined by the amount of carbon and other alloying elements in the metal.

Iron transforms from a face-centred cubic (FCC) structure, called the gamma phase, or austenite, at high temperatures to a body-centred cubic (BCC) structure-alpha phase, or ferrite, at a lower temperature. In a bar of pure iron, this transformation is marked by a distinct increase in length as the metal cools below the critical temperature, because the body-centred lattice is less compact than the face centred lattice. The high- temperature austenite, or FCC structure, allows enough space for carbon to squeeze in between the iron atoms. Iron atoms maintain their place on the lattice and carbon atoms become "interstitials". In the low-temperature ferrite, or BCC structure, however, there is no room for carbon atoms. What happens to these carbon atoms, determines many of the properties of iron and steel.

Finally, at about 1350°F, the lower end of the transformation temperature range for 1020 steel, the last remaining austenite tries to transform in spite of the rich carbon concentrations. At this point, two things occur. The carbon bonds with available iron atoms to form Fe_3C, an intermetallic compound called cementite or iron carbide, and precipitates out as a discrete structure; and then the remaining austenite transforms to ferrite. The structure that results from this final transformation is a laminate consisting of alternating layers of ferrite and iron carbide. Of course, the portions of metal that transformed previously remain as large islands of pure ferrite. The laminated structure formed at the last moment is called pearlite. The combined structure of ferrite and pearlite is soft, ductile, and generally represents steel in its lowest strength condition. In contrast, when ferrous alloys are cooled rapidly, e.g. by quenching, expelled carbon atoms do not have time to move away from the iron as it transforms to ferrite. The steel becomes so rigid that, before the carbon atoms have a chance to move, they become trapped in the lattice as the iron atoms try to transform to the body centred cubic structure. The result is a body centred tetragonal structure in which the carbon atom is an interstitial member. Steel that has undergone this type of transformation is called martensite. Naturally martensite is in a state of disequilibrium, but owes much of its high strength and hardness (but lower ductility) to its distorted, stressed lattice structure. Figure 2.4 shows a typical phase diagram for iron and iron carbide.

2.2 PHYSICAL AND MECHANICAL PROPERTIES OF METALLIC MATERIALS

Mechanical properties are defined as the properties of a material that reveal its elastic and inelastic (plastic) behaviour when force is applied, thereby indicating

its suitability for mechanical applications; for example, modulus of elasticity, tensile strength, elongation, hardness, and fatigue limit. Other mechanical properties, not mentioned specifically above, are yield strength, yield point, impact strength, and reduction of area, to mention a few of the more common terms. In general, any property relating to the strength characteristics of metals is considered to be a mechanical property. Physical properties relate to the physics of a metal, such as density, electrical properties, thermal properties, magnetic properties and the like.

A brief mention has been made of some of the properties of metallic materials in the previous section. These and other properties will be described here in slightly more detail.

2.2.1 Elasticity

When stress or force is applied to a metal, it changes shape. For example a metal under a compressive stress will shorten and metal in tension will lengthen. This change in shape is called strain. The ability of metal to strain under load and then return to its original size and shape when unloaded is called elasticity. The elastic limit (proportional limit) is the greatest load a material can withstand and still spring back into its original shape when the load is removed. Within the elastic

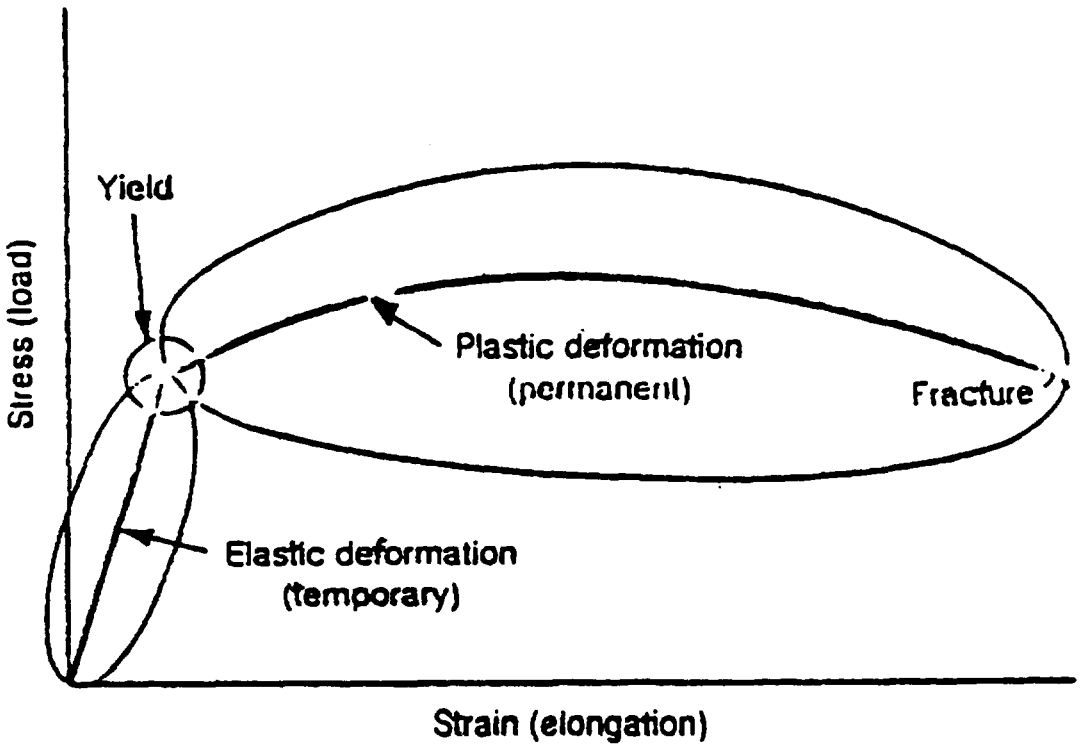

Figure 2.5 : Stress-strain curve showing elastic and plastic portions of a typical curve.

range stress is proportional to strain and this is known as Hooke's law. The relationship between applied stress or load and the consequent strain or change in length is shown in Figure 2.5. The end of the straight line portion is known as the elastic limit. A point on the curve slightly higher than the elastic limit is known as the yield point or yield strength. The allowable or safe load for a metal in service should be well below the elastic limit. If higher loads are applied, however, the range of elasticity or elastic deformation is exceeded and the metal is now permanently deformed. Now it will not return to its original dimensions even when the load is removed. For this reason, the area of the stress strain curve beyond the elastic limit is called the plastic range. It is this property that makes metals so useful. When enough force is applied by rolling, pressing or hammer blows, metals can be formed when hot or cold into useful shapes. If the application of load is increased in the plastic region a stage comes when the material fractures.

A very important feature of the stress-strain curve is that the straight-line or elastic part of the stress- strain curve of a given metal has a constant slope. That is, it cannot be changed by changing the microstructure or heat treatment. This slope, called the modulus of elasticity, measures the stiffness of the metal in the elastic range. Changing the hardness or strength does not change the stiffness of the metal. There is only one condition that changes the stiffness of any given metal. That is temperature. The stiffness of any metal varies inversely with its temperature; that is, as temperature increases, stiffness decreases, and vice versa.

The above comments on the elastic portions of the stress-strain curves apply to nearly all metals. However, there are a few metals that do not conform to Hooke's law. The reason in some cases, e.g. grey cast iron, is the presence of graphite flakes embedded in the matrix of the metal. The flakes act as internal notches or stress concentrations and therefore give the metals unique and different properties. Typical other example of such metals are sintered metals and cold drawn steel bars.

2.2.2 Strength

The strength of a metal is its ability to resist change in shape or size when external forces are applied. There are three basic types of stresses namely tensile, compressive, and shear. When we consider strength, the type of stress to which the material will be subjected must be known. Steel has equal compressive and tensile strength, but cast iron has low tensile strength and high compressive strength. Shear strength is less than tensile strength in virtually all metals.

The tensile strength of a material can be determined by dividing the maximum load by the original cross -sectional area before testing. Thus

$$\text{Tensile strength} = \frac{\text{Maximum load}}{\text{Original cross-sectional area}}$$

Metals are "pulled" on a machine called a tensile tester. A specimen of known dimensions is placed in the machine and loaded until it breaks. Instruments are sometimes used to make a continuous record of the load and the amount of strain (proportional change in length). This information is put on a graph called a stress–strain diagram. A stress-strain diagram can be made for any metal. The cross-sectional area to be pulled is usually a standard diameter of which the area can be easily calculated in round numbers. If a strain gauge and an XY recorder are used, the diagram is automatically made. If no recorder is available, the tensile testing machine may be stopped at intervals and the load, or stress, written down and the strain or distance between centerpunched marks measured and copied down on the same line. With some equipment, readings may be taken without stopping the machine. Later, these stress- strain increments can be plotted on a graph to produce the stress-strain diagram for that particular metal.

2.2.3 Hardness

The hardness of a metal is its ability to resist being permanently deformed. There are three ways that hardness is measured; resistance to penetration, elastic hardness, and resistance to abrasion. Hardness varies considerably from material to material. This variation can be illustrated by making an indentation in a soft metal such as aluminium and then in a hard metal such as alloy tool steel. The indentation could be made with an ordinary centre punch and a hammer, giving a light blow of equal force on each of the two specimens. In this case just by visual observation one can tell which specimen is harder. Of course, this is not a reliable method of hardness testing, but it does show one of the principles of hardness testers i.e. measuring penetration of the specimen by an indenter or penetrator, such as a steel ball or diamond point.

Rockwell and Brinell hardness testers are the most commonly used types of hardness testers for industrial and metallurgical purposes. Heat treaters, inspectors, and many others in industry often use these machines. The Rockwell hardness test is made by applying two loads to a specimen and measuring the difference in depth of penetration in the specimen between the minor load and the major load. The minor load is used on the standard Rockwell tester to eliminate errors that could be caused by specimen surface irregularities. The major load is applied after the minor load has seated the indenter firmly in the work. The Rockwell hardness reading is based on the additional depth to which the penetrator is forced by the major load. The depth of penetration is indicated on the dial when the major load is removed. The amount of penetration decreases as the hardness of the specimen increases.

Generally the harder the material is, the greater is its tensile strength, that is, its ability to resist deformation and rupture, when a load is applied.

The Brinell hardness test is made by forcing a steel ball, usually 10 millimetres (mm) in diameter, into the test specimen by using a known load weight and measuring the diameter of the resulting impression. A small microscope is used to measure the diameter of the impressions. Various loads are used for testing

different materials. These are typically 500 kilograms (kg) for soft materials such as copper and aluminium and 3000 kg for steels and cast irons.

2.2.4 Brittleness

A material that will not deform plastically under load is said to be brittle. Excessive cold-working causes brittleness and loss of ductility. Cast iron does not deform plastically under a breaking load and is therefore brittle

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A very sharp "notch" that concentrates the load in a small area can also reduce plasticity. Notches are common causes of premature failure in parts. Weld undercut, sharp shoulders on machined shafts, and sharp angles on forgings and castings are examples of unwanted notches (stress raisers).

2.2.5 Ductility

The property that allows a metal to deform permanently when loaded in tension is called ductility. Any metal that can be drawn into a wire is ductile. Steel, aluminium, gold, silver, and nickel are examples of ductile metals.

The tensile test is used to measure ductility. Tensile specimens are measured for area and length between gauge marks before and after they are pulled. The per cent of elongation (increase in length) and the per cent of reduction in area (decrease of area at the narrowest point) are measures of ductility. A high per cent elongation (about 70 per cent) and reduction in area indicates a high ductility. A metal showing less than 20 per cent elongation would have low ductility.

2.2.6 Malleability

The ability of a metal to deform permanently when loaded in compression is called malleability. Metals that can be hammered or rolled into sheets are malleable. Most ductile metals are also malleable, but some very malleable metals such as lead are not very ductile and cannot be drawn into wire easily. Metals with low ductility, such as lead, can be extruded or pushed out of a die to form wire and other shapes. Some very malleable metals are lead, tin, gold, silver, iron and copper.

2.2.7 Notch toughness

Notch toughness (impact strength) is the ability of a metal to resist rupture from impact loading when there is a notch or stress raiser present. A metal may show high ductility or strength when tensile tested or be hard or soft when hardness tested, but often the behaviour of metals under shock loads is not seemingly related to those properties. Of course, as a rule, a brittle metal such as grey cast iron will fail under low shock loads; that is, its shock resistance is low, and soft wrought iron or mild steel has a high shock resistance. But soft, coarse- grained

metals will have lower shock resistance than fine-grained metals. A notch or groove in a part will lower the shock resistance of a metal, so a specific notch shape and dimension is machined on the test specimen in order to give uniform results.

In general, the tensile strength of a metal changes in proportion to hardness. However, this relationship does not always hold true at high hardness levels or with brittle materials because these materials are more sensitive to stress concentrations, or notches, and may fracture prematurely when stressed in tension.

The harder and stronger the metal, the more sensitive it is to stress concentrations. Therefore, high hardness, high-strength metals must be treated carefully; virtually everything becomes critical because such metals cannot easily tolerate stress concentrations. They cannot flow, or deform plastically at the highly stressed regions of the stress concentrations as readily as more ductile metals of somewhat lower hardness. However, high hardness, high-strength metals are extremely useful when carefully used, because of their high static and fatigue strength as well as their high wear resistance.

2.2.8 Conductivity

Conductivity is a measure of the ability of a material to conduct electric current. It is the reciprocal of resistivity. Conductivity is commonly expressed as mhos per metre since the unit of resistivity is the ohm. The conductivity of metallic elements varies inversely with absolute temperature over the normal range of temperatures but at temperatures approaching absolute zero the imperfections and impurities in the lattice structure of a material make the relationship more complicated. Metals and materials exhibit a wide range of conductivities. Between the most conductive substances (silver and copper) and the most resistive (polystyrene for example) the difference amounts to 23 orders of magnitude.

The conductivity of materials can be explained as being due to the flow of loosely bound electrons which act as carriers and are free to wander through the solid. These electrons are mostly the valence electrons in the outer electronic shells of atoms. The difference between conductors and non-conductors can be explained in terms of the relative availability of carrier electrons. In the case of copper, a metal with a single valence electron, the electron is spread out in a cloud like orbit around the nucleus. In a crystal of copper in which the atoms are tightly packed together the electrons spread themselves throughout the entire lattice. They find this energetically favourable because according to the uncertainty principle their delocalization lowers their kinetic energy. It is this effect that causes the atoms in the crystal to stick together. Such delocalized electrons are ready candidates for acceleration in an electric field. In contrast to copper the atoms of the semiconductor germanium are cemented together more favourably by forming covalent bonds. In the resulting diamond like structure the electrons are not free to wander through the crystal or act as electrical carriers. Accordingly at absolute zero germanium would be an insulator. If however sufficient energy

(in the form of heat or light) is supplied to break some of the chemical bonds and so release electrons germanium becomes a conductor.

2.3 BASIC METALLURGICAL PROCESSES AND DEFECTS

Although it is not generally considered to be a part of non-destructive testing, a reasonable working knowledge of methods of fabrication is necessary for the NDT person to appreciate the types and likely locations of faults when a particular form of fabrication is used. It is, perhaps, as important for the designer to understand the possibilities and limitations of NDT and for both parties to be involved in the early design stages of a project to ensure that the final result can be inspected satisfactorily.

2.3.1 Welding processes

Welding can be defined as the metallurgical method of joining, applied to the general problem of construction and fabrication. It consists of joining two pieces of metal by establishing a metallurgical atom-to-atom bond, as distinguished from a joint held together by friction or mechanical interlocking. This metallurgical atom-to-atom bond is achieved by the application of heat and sometimes pressure.

Welding processes may be classified according to the source of energy employed for heating the metals and the state of metal at the place being welded. If the process is classified on the basis of heat source, which is the usual practice, the main headings, would be the 'electric arc', 'electrical resistance' and 'organic fuel'. The metallurgist classifies welding processes on another basis. In making a joint two parts of the same chemical composition may be welded together using no added metal to accomplish the joint. This might be termed as 'autogenous' welding. A metal which is of the same composition as the parts being joined may be added, in which event, the process would come under the general heading 'homogenous' welding. Finally, an alloy quite different from that of which the parts are made may be used or alternatively the parts themselves may differ significantly in composition. Then this process is called 'heterogeneous' welding. This approach to classification is most useful in studying the properties of welded joints but is not so advantageous as the preceding one in studying the processes themselves. Since it is of interest to study the processes rather than the properties of the joints the classification based on the heat source employed for welding will be adhered to. Figure 2.6 outlines the various welding processes some of the most commonly used of which are described here in some detail.

2.3.1.1 Oxy-fuel gas welding

Gas welding is a chemical process of welding in which the required heat is produced by the combustion of a mixture of two gases. The two gases are mixed in proper proportions in a welding blow pipe or torch which is designed so that

the operator has complete control of the welding flame. Common mixtures of gases are oxygen and acetylene, oxygen and hydrogen, and other fuel gases like, butane, propane, etc. and air and acetylene.

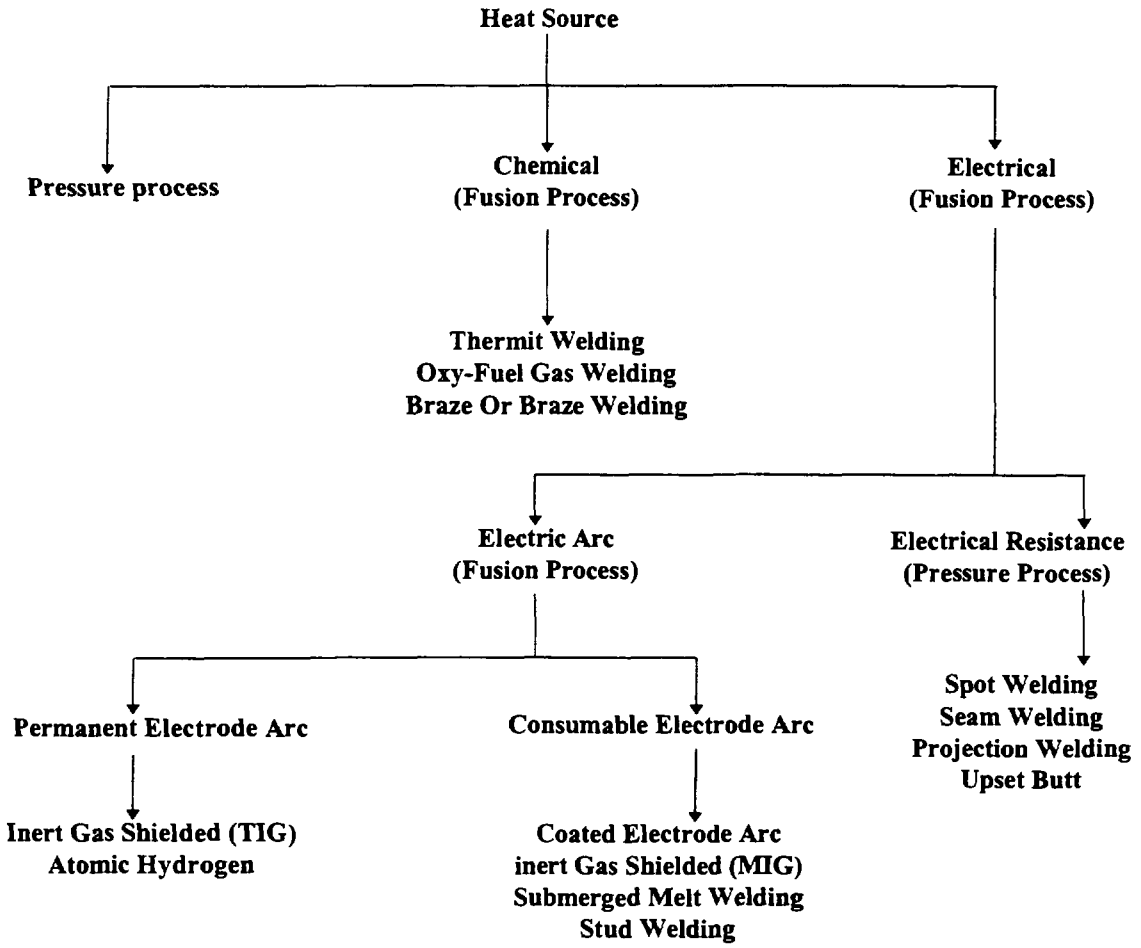


Figure 2.6 : Different processes of welding.

The oxygen acetylene mixture is used to a much greater extent than the others and has a prominent place in the welding industry. It is designated by the term oxy-acetylene welding.

Oxy-acetylene welding is a form of fusion welding wherein the heat required is supplied by the oxy-acetylene flame. Usually in the fusion process of welding a filler metal is added in the form of a welding rod to form the welded joint, although joints in some instances are formed in oxy-acetylene welding merely by fusing together the parts to be joined without the addition of the welding rod. Flux is employed in the welding of some metals as a means of floating out impurities or as an aid in obtaining a satisfactory bond.

The oxy-acetylene welding process is used in practically all the metal working industries. It is widely employed in such fabricating industries as sheet metal, tubing, aircraft, industrial piping and automotive, in laying pipelines, in shipyards, and for maintenance and repair purposes.

2.3.1.2 Electric arc welding

The electrical source of energy is used for heating the parts to be joined. This heat is produced by an electric arc between the metal pieces and an electrode of consumable or nonconsumable nature. The heat liberated at the arc terminals and in the arc stream is used to melt the metals to be welded at the point of contact, so that they will flow together and form a solid integral mass. Thus, different parts may be joined, or material may be added to the surface of a metal.

The arc welding processes fall naturally into two groups. Those in which the electrode melts and becomes a part of the weld and those in which the electrode is permanent. Hundreds of different alloys are suitable for the manufacture of consumable electrodes, but only tungsten and graphite meet the requirements for nonconsumable or permanent electrodes, and that is why consumable arc processes are by far the more important industrially.

An example of the permanent electrode arc welding process is inert gas shielded tungsten arc (TIG) welding. In TIG welding a tungsten electrode is used because of its lower burn off rate. The arc is struck between the tungsten electrode and the work. The atmosphere is either argon or helium. A filler rod may or may not be required, but usually it is needed while welding heavier sections. The inert gas, argon or helium, prevents oxidation of the molten metal by excluding oxygen from it.

The gas is fed through a nozzle surrounding the electrode in the head of a suitably designed electrode holder. The flowing inert gas completely envelops the lower end of the electrode and the work to exclude or physically displace the atmosphere from the molten metal. The total shielding of the system from air contamination prevents the formation of oxides, nitrides, and other compounds which tend to reduce the strength of the welded joint.

Among the consumable electrode processes are coated electrode welding, inert gas shielded metal arc (MIG) welding, submerged metal arc welding and stud welding. Since molten steel has an affinity for oxygen and nitrogen, when it is exposed to the air, it enters into chemical combination with the oxygen and nitrogen of the air to form oxides and nitrides in the steel. These impurities weaken and embrittle the steel and lessen its resistance to corrosion. To avoid these impurities in the weld the joint is shielded by a suitable shielding material. This may be a gas, a flux or some shielding material coated on the electrode. The electrode used in this process serves as a filler rod and is consumed by melting into the weld along with the flux which has been provided as a coating. The coating also helps to form and raise the slag to the top of the weld.

The basic principle of MIG welding is the same as that of coated electrode welding except that shielding in this case is provided by an inert gas, mostly helium or argon. The electrode is melted like the base metal by the intense heat of the arc produced between the filler metal (electrode) and base metal (work). Inert gas is supplied from an independent source, and is guided around the weld joint and the lower end of the electrode.

In the submerged arc welding process the welding area is shielded by a blanket of granular fusible material on the work. The granular material is usually called the melt or the flux. The filler metal is the current carrying conductor. It is usually a bare or coated wire. The flux spread over the area to be welded, is melted with the melting of the electrode and the work piece directly under it. The molten filler metal displaces this fluid flux and forms the weld. The fused flux floats to the top of the deposited metal and solidifies in the form of a brittle slag, which contracts upon cooling and is readily removable from the weld surface.

Stud welding is an arc welding process which in many respects resembles manual metal arc welding. The weld is effected by first drawing an electric arc between a stud (electrode) and the base material (work) to which it is to be welded and then bringing the two pieces in intimate contact when the proper temperature has been reached. The establishment of the arc, the determination of the welding time and the final plunging of the stud onto the work to complete the weld can be controlled automatically. Ordinarily in stud welding no shield of the weld zone is provided as in the case of inert gas shielded arc welding. However, the granular flux attached to the end of the welding stud does set up a reducing or protective atmosphere under nearly all welding conditions. Added protection is obtained from the porcelain or ceramic ferrule which surrounds the stud and the weld area and restricts the access of air to the weld zone. As a result of the combined shielding action, stud welding may be classified as a shielded arc-welding process.

2.3.1.3 Electrical resistance welding

Resistance welding is a process wherein two or more parts are welded together by the combined use of heat and pressure, and that is why this is classified as a pressure process of welding. The heat is generated by a relatively short-time flow of low voltage high density electric current across the intended joint location, and the pressure being supplied by contacting electrodes. These same electrodes also carry the current to the work pieces. Both electric current and pressure are closely regulated and controlled all the time.

Some of the sub-classifications of electrical resistance welding include 'spot welding', 'seam welding', and 'butt welding'. 'spot welding' is a resistance process of welding in which coalescence is produced by the heat obtained from resistance to the flow of an electric current through the workpieces pressed together by pointed electrodes. The electrodes are brought to and removed from the workpieces at predetermined times and rates, and a clamping force is applied

through the electrodes by some suitable means. The most widely used electrode material is pure copper, as it gives optimum results.

However, in general, relatively high conductivity electrodes should be used to weld low conductivity materials and low conductivity electrodes would be used on high conductivity materials. Moreover it should have enough compressive strength to withstand the applied welding pressures. In seam welding, electrodes in the form of rolls are used to transmit pressure and to send current through the overlapping sheet being moved between them. Interrupted current control is usually necessary since it provides better control of the heat, allows each successive increment in the seam to cool under pressure, and minimises distortion, flashes and burns. Butt welding is used to join lengths of rods and wire. The ends are pressed together and an electric current passed through the work so that the ends are heated to a plastic state due to higher electrical resistance existing at the point of contact. The pressure is sufficient to form a weld.

2.3.2 Weld defects

During the process of welding, defects of various types may occur. Some defects, such as those dealing with the quality and hardness of the weld metal, are subjects for the chemist and research worker, while others may be due to lack of skill and knowledge of the welder. These of course can be overcome by correct training of the welding operator. This latter field of defects is of concern here and will be discussed. The most common defects occurring in welds are given in the following:

2.3.2.1 Porosity

Molten weld metal has a considerable capacity for dissolving gases which come into contact with it such as hydrogen, oxygen and nitrogen. As the metal cools its ability to retain the gases diminishes. For instance, in steel the oxygen reacts with the carbon to form carbon monoxide, which is given off as a gas. With the change from the liquid to the solid state, there is reduced solubility with falling temperature. This causes an additional volume of gas to be evolved at a time when the metal is becoming mushy and therefore incapable of permitting the gas to escape freely. Entrapment of the gas causes gas pockets and porosity in the final weld. The porosity can be of three types namely 'fine porosity', 'blow holes' and 'piping'. Fine porosity consists of small bubbles of gas usually of diameter less than 1.6 mm. Blow holes are usually gas pores larger in dimension while 'piping' is an elongated or tubular cavity. Piping is usually almost perpendicular to the weld surface. It can result from the use of wet powdered flux or from inadequate regulation of the welding current. Another typical form of pipes has the appearance of a branch of a tree.

Porosity may be scattered uniformly throughout the weld, isolated in small groups or concentrated at the root of the weld. Various causes of porosity may include excessive moisture content of the electrode covering, incorrect electrode current, defective gas shielding, contamination of joint surface or filler wire and rapid

cooling of the weld metal or the composition of the parent metal or electrode core wire.

2.3.2.2 Non-metallic inclusions

These may be the result of weld-metal contamination by substances on the surface of the joint or by the atmosphere. But the usual source is the slag formed by the electrode covering or flux used in the welding process. Some slag may be trapped in the deposited metal during its solidification, particularly if the metal fails to remain molten for a sufficient period to permit the slag to rise to its surface. In multi-pass welding, insufficient cleaning between weld passes can leave a portion of the slag coating in place to be covered by subsequent passes. A particular characteristic of slag inclusions is the 'slag line', intermittent or continuous. Such slag lines are often accompanied by a pronounced lack of fusion to the base metal. In general, inclusions may be due to any one of several reasons which include failure to clean the surface of the joint, failure to remove slag from a previous deposit, incorrect edge preparation, incorrect manipulation of the electrode, insufficient arc shielding and improper rate of cooling.

2.3.2.3 Tungsten inclusions

Tungsten inclusions are particles of metallic tungsten embedded in the weld metal which originate from the tungsten electrode used in tungsten arc welding. Causes are excessive welding current allowing the melting and deposition of tungsten in the weld and incorrect polarity of electrode using a DC source. Tungsten inclusions can also be caused from dipping the electrode into the molten weld metal or by touching the filler rod to the electrode during welding. Tungsten inclusions frequently occur at the start of welds when the electrode may be cold. Small globular and widely scattered tungsten inclusions are sometimes permissible, but sharp edged inclusions are dangerous.

2.3.2.4 Lack of fusion

This is due to the lack of union in a weld between the weld metal and parent metal or between parent metal and parent metal or between weld metal and weld metal. Consequently the lack of fusion can be of three types namely lack of side fusion, lack of root fusion and lack of inter-run fusion. The defect results mainly from the presence of slag, oxides, scale, or other non-metallic substances, too low a welding current or incorrect edge preparation. Incomplete fusion can also arise from too high a welding current when the high melt rate encourages the welder to use excessive welding speed. The defect considerably reduces the strength of a joint subjected to static loading and under cyclic or shock loading it is quite serious.

2.3.2.5 Incomplete root penetration

In butt welding, a root opening is usually left at the bottom of the groove (in one-side welding) or at the centre of the weld (in two-side welding). If the opening between the two plates is narrow, it is difficult to achieve complete penetration and fusion at the root of the weld. Therefore there can be a lack of fusion in the

root of the weld or a gap left by the failure of the weld metal to fill the root of a butt weld. It is caused by the electrode held at an incorrect angle, an electrode too large in diameter, a rate of travel too fast, an insufficient welding current, or an improper joint preparation (e.g. joint misalignment).

2.3.2.6 Cracks

Cracks can be defined as a discontinuity produced either by tearing of the metal while in a plastic condition (hot crack) or by fracture when cold (cold crack). Cracks can occur in either the weld metal or parent metal. In the former they are classified as longitudinal, transverse, crater, and hairline cracks. In the latter it is cracking in the parent plate with the origin in the heat-affected zone of the weld. The strength of a welded joint under any conditions of loading will be seriously reduced by the presence of a crack. Weld metal cracks are caused by high localized stresses in the joint arising from the shrinkage of weld metal, by resistance of movement of the parts or by vibration of the structure during welding. Therefore it is important that each weld run is strong enough to withstand the shrinkage and allows as much freedom of movement as possible. Longitudinal weld cracks usually occur in the root run and, if left, will eventually propagate through subsequent runs. Incorrect finishing of a weld run can form a crater and possibly lead to a crater crack.

Parent metal cracking is associated with the welding of medium carbon and alloy steels. A considerable amount of research has gone into the techniques for welding these steels and it is most important that instructions regarding type and condition of electrode, the degree and extent of preheat and the restrictions on size of single pass welds are strictly observed to avoid this form of cracking.

2.3.2.7 Undercut

During the final or cover pass the exposed upper edges of the bevelled weld preparation tend to melt and to run down into the deposited metal in the weld groove. The result is a groove which may be either intermittent or continuous, with more or less sharp edges along the weld reinforcement.

2.3.2.8 Concavity at the root of the weld

A concave surface at the root of the weld can occur specially in pipe welding (without a cover pass on the root side). In overhead welding this condition is a consequence of gravity which causes the molten metal to sag away from the inaccessible upper surface of the weld. It can also occur in downhand welding with a backing strip at the root of the weld groove if slag is trapped between the molten metal and the backing strip.

2.3.2.9 Excessive penetration

In welds molten metal sometimes runs through the root of the weld groove producing an excessive reinforcement at the back side of the weld. In general this is not continuous but has an irregular shape with characteristic hanging drops of excess metal.

2.3.2.10 Overlap

Overlap is an imperfection at the toe or root of a weld caused by an overflow of weld metal onto the surface of the parent metal, without fusing with the latter. It is caused when the welding rod has been used at an incorrect angle, the electrode has travelled too slowly or the current was too low.

2.3.3 Casting processes

A commonly used method of forming metal objects of complex shapes is by pouring molten metal into a mould in which it sets to the required shape. The mould is then broken away to expose the casting, or the design of the mould is such that is can be separated without damage and re-used. The moulds are usually formed from patterns which can be used many times over, if necessary, and their design is critical in that 'feed' and 'vent' holes must be carefully positioned in the mould to permit the metal to flow freely into all parts. Problems that can occur are interaction on cooling. It is also unlikely that the crystal structure of a casting will be optimum in all parts so that its strength may be less than with other methods of fabrication. Various casting processes include 'sand die casting', 'permanent mould casting', 'centrifugal casting', 'investment casting' and 'shell mould casting'.

Since the casting process is complex and a large number of variables need to be controlled to get a good quality product and since it is not possible to give all the details here, only the principles and salient features of the above mentioned processes of casting are briefly presented.

2.3.3.1 Sand die casting

In this case a sand mould is used for casting the desired shape of the required alloy. A sand mould may be defined as a preformed sand container into which molten metal is poured and allowed to solidify. In general sand moulds are destroyed as the casting is removed from them. Sand moulds make it possible to cast complex shapes that might not be possible otherwise.

Different types of sand moulds can be made for making different castings. Green sand moulds are made from moist sand and are used for practically all ferrous and non-ferrous castings. They have the disadvantage of not being very strong as well as requiring moisture during manufacture which may cause certain defects in the casting. Green sand moulds may be provided with a dry sand on the surface to give

'skin-dry moulds'. Purely 'dry- sand moulds' can also be made by adding to the sand a binder instead of moisture. Its main advantages include a greater resistance to metal erosion, increased strength and a lessening of the tendency in the casting to acquire moisture-related defects. In some cases silica sand bonded with Portland cement may be used to make the moulds.

Methods of preparing sand moulds include 'bench moulding', 'machine moulding', 'floor moulding' and 'pit moulding'. 'Bench moulding' is used for

small castings. This is usually a slow and laborious process since hand ramming with loose pattern is usually used. Small and medium moulds may be made even with the aid of a variety of 'machines' which are usually faster and more uniform than bench moulding. Medium to large moulds are made directly on the foundry floor. Very large moulds made in a pit constructed for the purpose are called 'pit moulds'.

The sands most commonly used in 'sand die casting' contain silica sand which is usually from 50 to 95% of the total material in any moulding sand, zirconate and olivine, etc. The most important properties and characteristics of such sands are 'permeability', 'cohesiveness' and 'refractoriness'. Permeability is a condition of porosity and is related to the passage of gaseous material through the sand as well as to the density of sand grains. Cohesiveness can be defined as the holding together of sand grains or strength of moulding sand and depends upon the size and shape of the sand grains. The property of cohesiveness may be improved by adding to the sand some binders such as clay, resins and gums and drying oil. The third important characteristic of the moulding sand is 'refractoriness' which is its ability to withstand a high temperature without fusing. Pure silica sand can withstand a temperature as high as 3148°F. The property of 'refractoriness' can be affected by impurities like metallic oxides.

Mould cavities may be produced by packing the moulding material around what are called 'patterns'. The 'patterns' may be made from wood, metal or other suitable materials. There are a variety of these patterns used in the manufacture of castings. Another important part of the casting process is the 'core box' which is a structure made of wood, metal or other suitable material, containing a cavity with the shape of a desired core. Making a sand mould involves the proper packing of moulding sand around a pattern. After the pattern is removed from the sand and the gating arrangement completed, the mould cavity is filled with molten metal to form the casting.

2.3.3.2 Permanent mould casting

A casting made by pouring molten metal into a mould made of some metallic alloy or other material of permanence is known as a permanent mould casting.

Grey cast iron and Meehanite with large graphite flakes are the most commonly used materials in the construction of permanent moulds. This common use is partly due to the ease with which they may be machined. Certain steels, particularly special alloy steels that are heat-treated, often have especially good resistance to erosion. They have excellent refractory properties. Some aluminium alloys on which the surface has been anodized, are also used as moulding materials. Anodizing produces Al_2O_3 which is very refractory and resistant to abrasion. These alloys are very easy to machine and possess a good chilling capacity. The mould is not destroyed on removing the casting and therefore can be re-used many times.

The advantages of 'permanent mould casting' are that the casting process requires less skill, needs less floor space, better tolerances can be maintained, surface

finish is improved, casting is not susceptible to the typical sand casting defects and production costs can be reduced by increasing the lot sizes. The disadvantages include the higher cost of mould production in case of small production lots, the limited number of metals that are suitable to make moulds, the creation of undesirable stress problem due to the chilling effect of metallic moulds and the difficulty of casting ejection due to the rigid nature of the mould.

2.3.3.3 Centrifugal casting

Any process in which molten metal is poured and allowed to solidify while the mould is revolving, is a centrifugal casting process. Castings produced under this centrifugal force are called centrifugal castings. There are three recognized centrifugal processes namely 'true centrifugal casting', 'semicentrifugal or profiled-centrifugal casting' and 'centrifuged or pressure casting'. 'True centrifugal casting' is that in which castings are made in a hollow, cylindrical mould rotated about an axis common to both casting and mould. Cast-iron pipe is commonly made by this method. In this process the axis of spin may be horizontal, inclined, or vertical. In the true centrifugal casting process the inside circumference is always circular. When the mould is rotated on a horizontal axis, a true cylindrical inside surface is produced. True centrifugal casting is used only on symmetrically shaped objects. Semicentrifugal or profiled-centrifugal casting is similar to the true centrifugal method, except that a central core is used to form the inner surface or surfaces. The casting is not dependent upon centrifugal force for its shape. A good example of semicentrifugal work is a cast wheel-like casting. The axis of spin in the semicentrifugal process is always vertical. Although the yield is better than with static casting, it is not as high as in true centrifugal casting. With this process also only symmetrically shaped objects can be cast.

Centrifuged or pressure casting is applied for non-symmetrical castings. The mould cavity is not rotated about its own axis but about the axis of a central down sprue common to the axis of spin, which feeds metal into the mould cavity under centrifugal force. This process of centrifuging can be done only about a vertical axis. Centrifugal force provides a high pressure to force the metal alloy into the mould cavity.

Centrifugal casting processes can be used to produce parts made of both ferrous and non-ferrous alloy groups. Cast-iron pipe, gun barrels, automotive cylinder walls, jet engine rings, piston rings and brake drums are common parts centrifugally cast. Advantages include the elimination of foreign inclusions, better surface finish and the production of sounder castings. The chief disadvantages are the shape and size limitations.

2.3.3.4 Investment casting

This process involves making a one-piece mould from which the pattern is removed by a procedure which melts the pattern. The moulds used in this process are single purpose moulds. The elimination of all parting planes provides improved dimensional tolerances. Since the pattern is removed by melting or burning out, casting precision is increased through eliminating draft, rapping, and

shifts. Various other names are given to this process. It is also called 'precision investment casting', 'precision casting' or the 'lost-wax process'.

Various types and grades of wax are the common materials for pattern making for investment casting. Certain plastics that burn without residue are also used as pattern materials. Some low melting point metallic alloys can also be used as pattern materials. In this process of casting the patterns are formed afresh each time by casting or forging the pattern material in dies made of metal, plastic, rubber or wood. There are a number of materials applicable as investment material. These are actually the moulding materials, but due to the process used they are called investment material. Fine grained silica sand with a suitable binder is often used. Plaster of Paris and other gypsum products serve well as a binder for investment moulds used in the casting of non ferrous alloys. Other binders may include sodium silicate and various organic or inorganic chemical substances which satisfy specific applications. The investment materials are usually mixed into a fairly fluid slurry which is poured into place and vibrated to promote uniform packing and removal of air bubbles.

Patterns are first made of wax or other pattern materials by melting and then injecting it into a metallic or non metallic die. Then the patterns are welded or joined to gates and runners, which are also of the same material as the pattern. By this welding or joining of the pattern to gates and runners a tree like pattern is prepared. This tree is now dipped into a refractory sand, placed in a metal flask and sealed to the pallet. Then the investment or moulding material, in viscous slurry form, is poured around the pre-coated tree. When the investment has set, the mould is heated by putting it in an oven at 200^{o}F. By this heating the mould is dried and baked and the pattern is melted and the molten pattern material is taken out of the mould. Now as a final touch to the mould before casting the mould is placed in a furnace and is heated to a temperature of 1300–1900^{o}F. This removes all the wax residue, if any, sticking to the investment mould. The mould is then heated to the casting temperature.

In general investment castings have high precision and extremely smooth surfaces are easily produced. The process also makes possible the elimination of most machining operations and provides for an increased yield. Investment casting is adaptable to more complex and smaller designs in both limited as well as production lots. All metallic alloys can be cast with this process of casting. On the other hand the process is often more costly since materials as well as moulds are single purpose. Casting of large objects is impracticable, the operators need to be more skilled and more technically trained and the production cycle is a relatively slower one.

2.3.3.5 Shell moulding process

This process involves making a mould that has two or more thin, shell-like parts consisting of thermosetting resin-bonded sand. These shells are single purpose in application and are hard and easily handled and stored. Shells are made so that matching parts fit together easily, held with clamps or adhesives and poured in

either a vertical or horizontal position. These moulds may be supported in racks or in a mass of bulky permeable material like sand, steel shots, or gravel.

Metallic patterns are used for the production of shells, as they are subjected to heating temperatures approaching 1000°F. The pattern must have some provision, in the form of ejector pins, for the removal of shells from the surface of the pattern. Clean dry silica sand is the bulk material used in the making of shell moulds. Grain size and distribution can vary with use. Thermosetting synthetic resins are used as binders for sand. The resins include, the phenol formaldehydes, urea formaldehydes, and others.

The sand and resin mix or coated sand is caused to fall against, or is blown against, a heated metal pattern or core box. The temperature of the pattern ranges from 350–600°F. Contact of the thermosetting resin with the hot pattern causes an initial set and thus an adhering layer of bonded sand is formed within 5 to 20 seconds. The pattern with this adhering layer of bonded sand is placed into the furnace and is cured by heating to the proper temperature for from one to three minutes. The time of curing depends on the shell thickness and the resin type. The assembly is then removed from the furnace and the shell is stripped from the pattern by ejector devices. This stripping is sometimes a problem and can be overcome by using a silicon parting agent.

The main advantages of this process are that the 'shell' cast parts have generally a smooth surface and thereby reduce machining costs. These techniques are readily adaptable to mass production by using automatic equipment. The disadvantages can be the initial cost of metal patterns, the higher cost of the resin binders and a general size limitation.

2.3.4 Casting defects

Casting defects may be defined as those characteristics which create a deficiency or imperfection exceeding quality limits imposed by design and service requirements. There are in general three broad categories of these defects. First are the major or most severe defects which result in scraping or rejection of the casting. The second category is of intermediate defects which permit salvaging of the casting through necessary repair. The third category defects are minor ones which can be easily repaired. The elimination and control of casting defects is a problem that the foundry engineer may approach in several ways. The common procedure is to rely in salvaging techniques that appear to provide immediate savings. Remedial procedure in the moulding, coremaking, melting or pouring areas of the foundry are frequently neglected but are highly desirable to be controlled to avoid defects. Some of the defects which usually occur in castings are given here under :

2.3.4.1 Porosity

Gas holes are spherical holes of varying size, with bright walls, usually fairly evenly distributed and formed by gas in the metal. The larger holes tend to be found in the heavier section (i.e. last to solidify). If the metal is correct prior to

casting, the pinhole type of porosity is probably due to absorption of hydrogen from steam in the mould. The gas in the molten metal is removed by a gas scavenging technique and by keeping casting ladles and moulds dry.

2.3.4.2 Blowholes

Blowholes are mainly found in three forms: i) Elongated cavities with smooth walls, found on or just below the surface of the topmost part of a casting. These are caused by entrapped air and repetition can be avoided by venting the mould and increasing its permeability. ii) Rounded shape cavities with smooth bright walls are caused by mould or core gases, coupled with insufficient permeability or venting. They can be avoided by using less oil binder in the mould and ensuring that cores are dry and properly baked and that the sand is properly mixed. iii) Small cavities immediately below the 'skin' of the casting surface are formed by the reaction of the molten metal with moisture in the moulding sand. This can be avoided by reducing the volatile content in mould cores and mould dressing, by ensuring that metal is deoxidised, by using more permeable sands, by ensuring that moulds and cores are properly vented and by reducing pouring temperature.

2.3.4.3 Piping

When this term is used in the foundry it refers to the defects encountered in risers or within the casting proper.

2.3.4.4 Inclusions

These are material discontinuities formed by the inclusion of oxides, dross, and slag in a casting. They are due to careless skimming and pouring, or the use of a dirty ladle, or to turbulence due to improper gating methods when casting alloys, such as aluminium bronze, that are subject to surface oxide-skin formation. Faulty closing of moulds can cause 'crush' and loose pieces of sand becoming incorporated in the casting. The occurrence of inclusions can be avoided by proper use of equipment and foundry practice.

2.3.4.5 Sponginess

A defect that occurs during the early stages of solidification of a casting and has the appearance, as the name would imply, of a sponge; it may be local or general in extent. The major cause is failure to obtain directional solidification of the casting towards the desired heat centres, such as risers and ingates; insufficiently high pouring temperature and placing of ingates adjacent to heavy sections.

2.3.4.6 Shrinkage

A casting defect that occurs during the middle and later stages of solidification of the cast metal. It has a branching formation, is readily distinguishable from that of sponginess, and is a form of void. The defect can be avoided by paying particular attention to the direction of solidification and ensuring adequate risers, or other feeding aids, on the heavier sections of a casting. Modification of casting design,

i.e. to make cast sections more uniform for the flow and solidification of the metal is helpful in avoiding shrinkage. Moulds and cores are sometimes made too strong and greatly resist the contraction of the cast metal and, in this way, will cause a breakdown in the homogeneity of the metal.

2.3.4.7 Hot tears

These are discontinuities that result from stresses developed close to the solidification temperature while the metal is still weak. These, again, are attributed to resistance of the mould and core, which hinder contraction of the casting, causing thermal stress. Hot tears resemble ragged cracks. They can be avoided by making cores and moulds more collapsible, avoiding abrupt changes in section and preventing the formation of intense hot spots by designing with more uniform sections.

2.3.4.8 Crack

Well defined and normally straight, they are formed after the metal has become completely solid. Quite large stresses are required to cause fracture, and the walls of such cracks are discoloured according to the temperature of the casting when the cracks formed. Bad casting design coupled with restriction of contraction by the mould, core, or box bars contribute to cracking, and avoidance of these, together with the easing of mould or cores as soon as possible after solidification, will help prevent build-up of stresses.

2.3.4.9 Cold shuts

These are discontinuities (a form of lack of fusion) caused by the failure of a stream of molten metal to unite with another stream of metal, or with a solid metal section such as a chaplet. They are linear in appearance, with perhaps a curling effect at the ends. A cold shut is caused by the fluidity of the metal being too low (i.e. surfaces too cold) or perhaps unsatisfactory methods of feeding the molten metal.

Cold shuts can often be avoided by raising the pouring temperature or pouring rate or both and reviewing the position, size, and number of ingates and the arrangements for venting the mould.

2.3.4.10 Unfused chaplet

A chaplet is often used to support a section of a mould or a core within a mould and when the molten metal is poured in the chaplets should fuse into the casting. When unfused the chaplet will cause a discontinuity in the casting. Design of chaplet and type of chaplet should be reviewed in overcoming this defect.

2.3.4.11 Misplaced core

An irregularity of wall thickness, e.g. one wall thicker than the other, can be detected by a double wall technique radiograph. It is caused by core out-of-

alignment, careless coring-up and closing of mould, or rough handling after the mould is closed.

2.3.4.12 Segregation

Segregation is a condition resulting from the local concentration of any of the constituents of an alloy. The segregation can be 'general' extending over a considerable part of a casting, 'local' when only the shrinkage voids or hot tears are wholly or partially filled with a constituent of low melting point or 'banded' which is mainly associated with centrifugal castings but can also occasionally occur in static castings.

2.3.5 Forging processes

Forging is the working of metal into a useful shape by hammering or pressing and is the oldest of the metal forming processes. Most forging operations are carried out hot, although some metals are cold-forged. The hot working of metals in the forging process results in an improvement in the mechanical properties. This method of shaping is therefore used in the manufacture of parts requiring good mechanical properties. Improvement in the mechanical properties results from a general consolidation of the metal and closing of gas and contraction cavities by means of mechanical pressure, a refinement of the crystal structure and a destruction of the continuity of intergranular concentrations of impurities and inclusions.

Forging is done on either a hammer or a press. A horizontal press (forging machine) is used in certain instances for forging small parts; otherwise forging machines are vertical, the lower die of which is fixed while the upper die is moveable, being carried on a vertical ram. In the case of hammers the die is raised mechanically and the blow is struck by the die falling freely. With presses, force is used to raise and lower the die and the metal is worked by slow, steady pressure. Forging is not only employed to produce parts of a shape that cannot be rolled but also for parts of simple uniform shape, round or rectangular, when these are large or when the quantity required is too small to warrant a roll set-up. Tool steels are often forged with a view to improving their properties.

Forging may be considered under two categories. First where the working surface of the dies is flat or of uniform curved contour and shaping is done by manipulation using tools of simple shape. This is called 'open-die' forging. The second is where impression dies are used and the metal is shaped by being forced into the die impressions. This is called 'closed-die' forging. In the first category are forgings of simple, round or rectangular cross-section and forgings of more complicated shapes which are so large that 'sinking' of closed dies would be impractical or too costly. Small forgings of complicated final shape may be rough forged on simple dies and then machined to final form if the number required is too small to justify the cost of an impression die. In this category also are hollow forged parts. For these, the centre metal of the rough piece of proper size is either machined out cold (trepanned), or is punched out hot using suitable dies on a press. The part is then forged on a mandrel passing through the centre hole and supported at both ends so that the mandrel acts as the bottom die. In closed die

forging on a hammer or vertical press the lower die has an impression corresponding to one half of the part to be made while the upper die has an impression corresponding to the other half. For relatively simple shapes the dies may have only one impression but more commonly they incorporate a series of impressions in which the part is successively shaped to the final form. Closed die forging is commonly known as 'drop forging'. Around the impressions the dies are shaped to provide space for the excess stock, as it is not practical to have exactly the amount of metal required to fill the impressions. The excess metal that is forced into this space is referred to as 'flashing' or 'flash'. After forging this is trimmed off in suitable dies. The closed die forging business is so competitive that the losses in trim scrap provide one of the most important areas for economy.

The hot forging process whereby bolts, for example, are headed is referred to as hot upset forging or hot heading. In this process, a bar of uniform cross section is gripped between grooved dies and pressure is applied on the end in the direction of the axis of the bar by means of a heading tool. The metal flows under the applied pressure and fills the cavity between the dies.

2.3.6 Rolling processes

The flattening of metal between rollers is used for the production of strip, sheet, plate, bar and sections. Since the metal is formed by a squeezing action, rolling can be considered as a continuous forging process with the rolls acting as hammers and the metal being drawn down.

Rolling may be performed above the temperature of recrystallisation (hot rolling) or below the temperature of recrystallisation (cold rolling). Hot rolling is always used for the initial rolling of the cast ingot. Not only is it easier to break down the ingot to size quickly when it is hot and plastic, but the hot-rolling process closes any casting discontinuities and forge welds their surfaces together. This prevents any faults, which could lead to lamination, being carried forward into subsequent rolling operations. In hot rolling the coarse grains are first elongated and distorted and then formed into equi-axed crystals due to recrystallisation. The crystals elongated and distorted by cold rolling do not recrystallise and the metal therefore remains work-hardened.

Rolling mills are described according to the arrangement of the rolls. The simplest is the two-high reversing mill. In this the metal is passed through from one side, the rolls are then lowered and their direction of rotation is reversed, and the metal is passed back through them. This cycle is repeated until the metal is of the required thickness. In the three-high mill the rolls rotate continuously in one direction. The roller beds rise and fall to pass the metal between the lower two rolls first and then back again between the upper two rolls. The cycle is repeated until the metal is of the required thickness. In the four-high mill and the cluster mill the additional rolls 'back up' the working rolls and allow them to apply greater pressure on the metal being rolled without deflection. Four-high and cluster mills operate in the same manner as the two-high reversing mill, and are widely used for cold rolling bright finished strip. Some typical rolling-mill processes are slabbing, cogging and re- rolling. Slabbing is the process of breaking down the ingot into slabs ready for re-rolling into strip, sheet and plate.

The process is carried out at 1300°C and casting discontinuities in the ingot are welded by the process thus making the slab homogeneous. Cogging is similar to slabbing except that the ingot is rolled into 'blooms' ready for re-rolling into bars and sections. Two-high and four-high reversing mills are usually used for rolling both slabs and blooms. The re-rolling of slabs into strip is usually performed in a continuous strip mill. The slab is reheated to 1300 °C and passed through a water spray and scale-breaking rolls to remove the scale left on the surface of the slab from previous processing. It is then roughed down, and finally passed to the finishing 'train' of rolls. The strip is finally coiled ready for further processing. The re-rolling of sections and bars is usually performed in two-high reversing mills fitted with grooved rolls. Some modern plants handling large quantities of standard section beams and joints are often laid out to provide a continuous train.

Whilst materials that are forged into wire and tube require the property of malleability, materials that are drawn into wire and tube require the property of ductility, combined with a relatively high tensile strength and a low work-hardening capacity as the process is performed cold. The reduction in size of the drawn section is provided by the material being pulled through a die. Rods and bars are drawn using draw-benches.

Fine wire, especially the copper wire used for electrical conductors, is drawn on multiple-die machines. A capstan block pulls the wire through each die and passes it onto the next stage in the machine. As the wire becomes finer its length increases and the speed of the last capstan has to be very much higher than the first.

Tube drawing is similar to rod drawing using a draw bench. However, the billet is pierced to start the hole and the tube is drawn over a mandrel. Where longer lengths of tube are required, the stock and the drawn tube have to be coiled. This prohibits the use of a fixed mandrel, and a floating mandrel or plug is used.

Another process which is similar to rolling is extrusion. In principle, extrusion is similar to squeezing toothpaste from a toothpaste tube. The raw material is a heated cast billet of the required metal. Usually this is either a copper alloy, an aluminium alloy or lead. The pressure necessary to force the metal through the die is provided by the hydraulic ram. Since the billet is reduced to the size of the finished section in one pass through the die, extrusion is a highly productive process. However, the plant is extremely costly and so is its operation and maintenance. Like most hot processes the finish and dimensional accuracy of the section is lower than that associated with cold drawing. Therefore, where greater accuracy is required, the extruded section is given a light draw to strengthen the section and improve its finish and dimensional accuracy.

2.3.7 Forging and rolling defects

Discontinuities in forgings may originate in the slab or billet and be modified by the rolling and forging of the material, or may result from the forging process itself. Some of the defects that can occur in forgings are similar to those in

castings since most forgings originate from some form of cast ingot. Given below are some of the more specific defects.

2.3.7.1 Laminations

Large porosity, pipe and non-metallic inclusions in slabs or billets are flattened and spread out during the rolling and forging processes. These flattened discontinuities are known as laminations.

2.3.7.2 Seams

Surface irregularities, such as cracks, on the slab or billet are stretched out and lengthened during rolling and are then called seams. Seams may also be caused by folding of the metal due to improper rolling. Seams are surface discontinuities and on finished bars will appear as either continuous or broken straight lines. On round bar stock they will appear as straight or slightly spiral lines, either continuous or broken.

2.3.7.3 Forging laps

Forging laps are the discontinuities caused by the folding of metal in a thin plate on the surface of the forging. They are irregular in contour.

2.3.7.4 Centre bursts

Ruptures that occur in the central region of a forging are called centre bursts. They can arise because of an incorrect forging procedure (e.g. too low a temperature or too drastic a reduction) or from the presence of segregation or brittle phase in the metal being forged.

2.3.7.5 Clinks (thermal cracks)

Clinks are cracks due to stresses arising from excessive high temperature gradients within the material. Cracks formed during too rapid cooling originate at the surface and extend into the body of the forging; those formed during too rapid heating occur internally and can be opened up to become diamond-shaped cavities during subsequent forging.

2.3.7.6 Hairline cracks (flakes)

Flakes are very fine internal cracks of circular shape that develop and extend with time and are associated with the presence of hydrogen in steel. There is greater susceptibility in larger forgings than in smaller and in certain grades of alloy steel than in carbon steel; they can be avoided by correct treatment.

2.3.7.7 Hot tears

Surface defects due to metal being ruptured and pulled apart during forging. They may be associated with the presence of local segregation, seams, or brittle phases.

2.3.7.8 Stringers

Non-metallic inclusions in slabs or billets that are thinned and lengthened in the direction of rolling by the rolling process are called stringers.

2.3.7.9 Overheating

Normally identified by the facets seen on the fractured surfaces of a test-piece, but in extreme cases, can manifest itself as a severely broken-up surface.

2.3.7.10 Pipe

If there has been insufficient discard from the original ingot, remnant primary pipe will normally show up axially. Secondary pipe that has never been exposed to the atmosphere will be welded-up if there has been sufficient forging.

2.3.8 Surface finishing

Products that have been completed to their proper shape and size frequently require some type of surface finishing to enable them to satisfactorily fulfil their function. In some cases, it is necessary to improve the physical properties of the surface material for resistance to penetration or abrasion. In many manufacturing processes, the product surface is left with dirt, metal chips, grease or other harmful material on it. Assemblies that are made of different materials or from the same materials processed in different manners, may require some special surface treatment to provide uniformity of appearance.

Surface finishing may sometimes become an intermediate step in processing. For instance, cleaning and polishing are usually essential before any kind of plating process. Some of the cleaning procedures are also used for improving surface smoothness on mating parts and for removing burrs and sharp corners, which might be harmful in later use. Another important need for surface finishing is for corrosion protection in variety of environments. The type of protection provided will depend largely upon the anticipated exposure, with due consideration to the material being protected and the economic factors involved.

Satisfying the above objectives necessitates the use of many surface finishing methods that involve chemical change of the surface, mechanical work affecting surface properties, cleaning by a variety of methods and the application of protective coatings, organic and metallic.

2.3.8.1 Casehardening of steels

Casehardening results in a hard, shell like surface. Some product applications require surface properties of hardness and strength to resist penetration under high pressure and to provide maximum wear properties. Where through hardness and the maximum strength associated with it are not necessary, it may be more

economical to gain the needed surface properties by a casehardening process. Casehardening involves a change of surface properties to produce a hard, wear resistant shell with a tough fracture resistant core. This is usually accomplished by a change of surface material chemistry. With some materials, a similar condition can be produced by a phase change of the material already present.

Casehardening may be more satisfactory than through hardening in those cases where a low cost, low carbon steel with a hard shell can be used instead of a higher cost, high carbon or alloy steel which would be needed for through hardening. The process is much less likely to cause warping or cracking and the product, because of its soft ductile core, is less subject to brittle failure than a through hardened product. Case hardening is often suitable for heavy sections that would require very special high alloy steels for through hardening to be effective.

Case depth measurement is sometimes checked by destructive methods, cutting the object, etching the cut surface and checking the cut depth with a measuring microscope. A faster and more usable method when knowledge is needed directly for service parts, is to use eddy current tests.

2.3.8.2 Carburizing

Casehardening of steel may be accomplished by a number of methods. The choice between them is dependent on the material to be treated, the application and the desired properties. One of the more common methods is carburizing which consists of an increase or addition of carbon to the surface of the part. Carburizing is usually performed on a low alloy or plain low carbon steel. If an alloy steel is used, it usually contains small quantities of nickel or some other elements that act as grain growth retarder during the heating cycle. Low carbon steels are commonly used to minimise the effect of subsequent heat treatment on the core material. It is possible to carburize any steel containing less than the 0.7% to 1.2% carbon that is produced in the surface material.

Carbon is caused to diffuse into the steel by heating the material above its critical temperature and holding it in the presence of excess carbon. The temperatures used are usually between 850°C and 930°C with the choice most dependent on the desired rate of penetration, the desired surface carbon content and the permitted grain growth in the material. Penetration is dependent upon both the temperature and time, with variations of case depth from 0.25 to 1.0 millimetre (0.010 to 0.040 inch) possible in the first 2 hours by varying the temperature between the two extremes. The rate of penetration slows down as the depth increases, as shown in Figure 2.7, so that for large depth, relatively long periods of time are necessary.

The excess carbon for diffusion is supplied from a carbon rich environment in solid, liquid, or gas form. Parts to be carburized may be packed in carbon or other carbonaceous material in boxes that are sealed to exclude air and then heated in a furnace for the required length of time in a process sometimes called pack carburizing. The liquid method makes use of molten sodium cyanide in which the

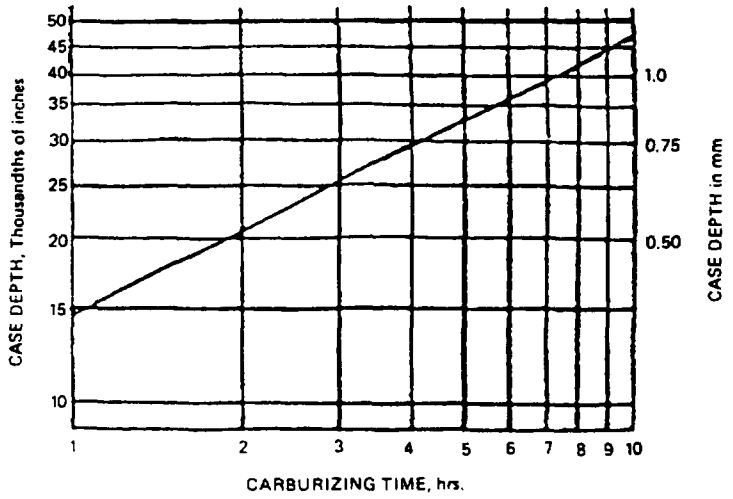


Figure 2.7 : Typical carburizing case depth–time relationship.

parts are suspended to take on carbon. The cyanide method is usually limited to shallow case depths of about 0.25 mm (0.010 in) maximum. The third method, often the most simple for production operations requiring a thick case depth, supplies gaseous hydrocarbons from an unburned gas or oil fuel source to the furnace retort in which the product is heated. The product is usually suspended on wires or rolled about so that all surfaces are exposed uniformly.

Carburizing steels containing grain growth inhibitors may be quenched directly from the carburizing furnace to harden the outside shell, but plain carbon steels must be cooled and reheated through the critical range to reduce grain size. Even the alloy steels will have better properties if treated in this manner. Quenching from above the critical temperature will produce a hard martensitic structure in the high carbon surface material but will have little or no effect on the low carbon core. As in the case of most through hardened steels, tempering is usually required to toughen the outside shell. The complete cycle for casehardening by carburizing is illustrated in Figure 2.8.

2.3.8.3 Flame hardening

Another case hardening process that does not require a change of composition in the surface material is flame hardening. This method can be used only on steels that contain sufficient carbon to be hardenable by standard heat treating procedures. The case is produced by selectively heating part or all of the surface with special high capacity gas burners or oxy-acetylene torches at a rate sufficiently high that only a small depth from the surface goes above the critical temperature. Following immediately behind the torch is a water quenching head that floods the surface to reduce the temperature fast enough to produce a martensitic structure. As in the case of carburizing, the surface may be then reheated to temper it for toughness improvement. The depth of hardness is controlled by the temperature to which the metal is raised, by the rate of heating, and by the time that passes before quenching.

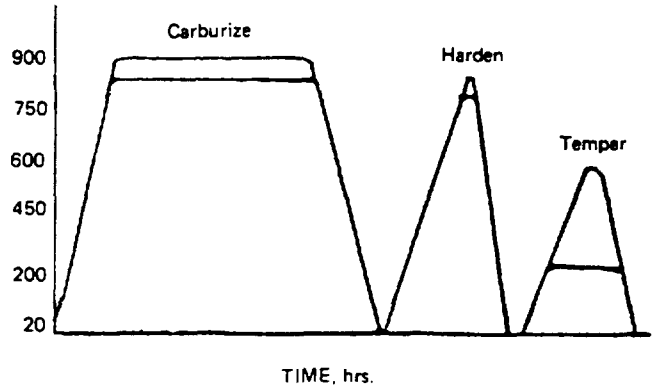


Figure 2.8 : Typical heat treatment cycle for carburizing.

2.3.8.4 Cleaning

Few if any shaping and sizing processes produce products that are suitable without some type of cleaning unless special precautions are taken. Hot working, heat treating, and welding cause oxidation and scale formation in the presence of oxygen. For the same reason, castings are usually coated with oxide scale. If they are made in sand moulds they may have sand grains fused or adhering to the surface. Residue from coolants, lubricants and other processing materials is common on many manufactured parts. In addition to greasy films from processing, protective coatings of greases, oils, or waxes are frequently used intentionally to prevent rust or corrosion on parts that are stored for some period of time before being put to use. Even if parts are clean at the completion of manufacturing, they seldom remain that way for long. After only short storage periods, corrosion and dust from atmospheric exposure necessitate cleaning particularly if further processing is required.

When using NDT methods such as penetrant testing and ultrasonic testing good precleaning may be necessary to get accurate results and postcleaning is often needed to leave the surface in a suitable condition. In some applications such as on stainless steels and nickel based alloys, ultrasonic couplants and penetrant materials must be made of only certain materials so that they do not cause stress corrosion failure.

Cleaning sometimes has finish improvement associated with it. Some shape producing methods produce unsatisfactory surface characteristics such as sharp corners, burrs and tool marks which may affect the function, handling ease, and appearance of the product. Some cleaning processes at least partially blend together surface irregularities to produce uniform light reflection. Improvement of surface qualities may be accomplished by removal of high spots by cutting or by plastic flow as cleaning is performed.

Many different cleaning methods are available. The most commonly used ones are briefly mentioned here : the most widely used cleaning methods use a cleaning medium in liquid form, which are applied to the object to be cleaned in different ways such as spraying, brushing or dipping the object in a bath of the cleaning liquid. Cleaning may be carried out through the process of blasting

wherein the cleaning medium which may be a liquid or a solid (e.g. sand, glass or steel beads, etc.) is accelerated to high velocity and impinged against the surface to be cleaned. A number of cleaning operations can be quickly and easily performed by use of wire brushes either manually or by rotating them at high speeds. The cleaned surface may be given a final polishing touch using a flexible abrasive wheel. Buffing is a kind of polishing process.

2.3.8.5 Coatings

Many products, in particular those exposed to view and those subject to change by the environment with which they are in contact, need some type of coating for improved appearance or for protecting from chemical attack. All newly created surfaces are subject to corrosion, although the rate of occurrence varies greatly with the material, the environment, and the conditions. For all practical purposes, some materials are highly corrosion resistant because the products of corrosion resist further corrosion. For example, a newly machined surface on an aluminium alloy will immediately be attacked by oxygen in the air. The initial aluminium oxide coating protects the remaining metal and practically stops corrosion unless an environmental change occurs. Corrosion rates are closely dependent on environment. Rates increase with rise of temperature and greater concentration of the attacking chemical. The need for corrosion protection for maintenance of appearance is obvious. Unless protected, an object made of bright steel will begin to show rust in a few hours of exposure to ordinary atmosphere. In addition to change of appearance, loss of actual material, change of dimensions, and decrease of strength, corrosion may be the cause of eventual loss of service or failure of a product. Material that must carry loads in structural applications, especially when the loads are cyclic in nature, may fail with fatigue if corrosion is allowed to take place. Corrosion occurs more readily in highly stressed material where it attacks grain boundaries in such a way as to form points of stress concentrations that may be nuclei for fatigue failure.

The correction for corrosion problems include choice of materials that resist attack from the environment to which they are exposed, selection or control of the environment to minimise corrosion effects and the use of selective corrosion by placing materials with greater susceptibility to corrosion near to those to be protected. The latter is illustrated by the use of magnesium rods in hot water tanks. The magnesium is the target for corrosion, as long as it is present, corrosion of the steel walls of the tank is insignificant. Another correction for corrosion, when the others are impractical, is the coating of the surfaces needing protection with a material that resists the environmental elements that are harmful. Thickness of coating may be important for many reasons. If the objective is improvement of appearance, uniformity of coating may be required, or lacking that, some minimum value may have to be surpassed to provide the appearance of uniformity. Life of a coating is usually also closely associated with uniformity and depth of coating layer. Many coatings are inherently porous to some degree and resistance to corrosion is likely to require thickness sufficient to resist penetration by liquids and gases. For those reasons manufacturing specifications frequently list minimum thickness for coatings and an NDT measurement is usually the only way to know whether that specification is being

met. Although other methods are possible, gauging with eddy current methods is common.

In addition to stabilizing appearance by resisting corrosion, coatings are often very valuable for providing colour control, changing appearance and providing variety which may be important in enhancing sales appeal. Some coatings such as fillers, paint and others with substantial body, improve surface smoothness by filling pores and cavities. Some coating materials can provide uniform appearance for products made as assemblies of different materials. Coating of various types may be used to change or improve surface properties. Case hardening of steel has been discussed earlier and although it is a surface property-changing method, in most of its forms, casehardening does not consist of the addition of a coating. Hardness and wear resistance can, however, be provided on a surface by plating with hard metals. Chromium plating of gauges subject to abrasion is frequently used to increase their wear life. Coatings of plastic materials and asphaltic mixture are sometimes placed on surfaces to provide sound deadening. The additional benefit of protection from corrosion is usually acquired at the same time.

2.3.8.6 Metallizing

Metal spraying, or metallizing, is a process in which metal wire or powder is fed into an oxy-acetylene heating flame and the same after melting, is carried by high velocity air to be impinged against the work surface. The small droplets adhere to the surface and bond together to build up a coating. The nature of the bond is dependent largely on the materials. The droplets are relatively cool when they make contact and in fact can be sprayed on wood, leather, and other flammable materials. Little, if any, liquid flow aids the bonding action. If, however, sufficient affinity exists between the metals, a type of weld involving atomic bonds may be established. The bond is largely mechanical in most cases and metal spraying is usually done on surfaces that have been intentionally roughened to aid the mechanical attachment. Zinc, aluminium, and cadmium, which are anodic to steel and therefore provide preferential corrosion protection, are usually sprayed in thin layers, averaging about 0.25 millimetre (0.010 inch) in thickness, as protective coatings. Because sprayed coatings tend to be porous, coatings of two or more times this thickness are used for cathodic materials such as tin, lead, and nickel. The cathodic materials protect only by isolating the base material from its environment.

Another important application for metal spraying is in salvage operations for which a wide variety of metals and alloys may be used. Surfaces, usually after first being roughened, are built up to oversized dimensions with metal spray. The excess material is then machined away to the desired dimension. Expensive parts with worn bearing surfaces or new parts that have been machined to undersize can sometimes be salvaged by this relatively cheap procedure.

Some metals can be deposited in very thin films, usually for reflective or decorative purposes, as a vapour deposit. The metal is vapourized in a high vacuum chamber containing the parts to be coated. The metal vapour condenses on the exposed surfaces in a thin film that follows the surface pattern.

Several metals, mainly zinc, tin, and lead, are applied to steel for corrosion protection by a hot dip process. Steel in sheet, rod, pipe, or fabricated form, properly cleansed and fluxed, is immersed in molten plating metal. As the work is withdrawn the molten metal that adheres solidifies to form a protective coat.

Coating of many metals can be deposited on other metals, and on non-metals by electroplating, when suitably prepared. This is based on the principle that when direct current power of high enough voltage is applied to two electrodes immersed in a water solution of metallic salt, current will flow through the circuit causing changes at the electrodes. At the negative electrode, or cathode (the work), excess electrons supplied from the power source neutralize positively charged metallic ions in the salt solution to cause dissolved metal to be deposited in the solid state. At the positive electrode, or anode (plating metal), metal goes into solution to replace that removed at the other electrode. The rate of deposition and the properties of the plated material are dependent on the metals being worked with, the current density, the solution temperature, and other factors.

2.3.8.7 Chemical treatment

A relatively simple and often fully satisfactory method for protection from corrosion is by conversion of some of the surface material to a chemical composition that resists attack from the environment. These converted metal surfaces consist of relatively thin (seldom more than 0.025 millimetre, or 0.001 inch thick) inorganic films that are formed by chemical reaction with the base material. One important feature of the conversion process is that the coatings have little effect on the product dimensions. However, when severe conditions are to be encountered , the converted surface may give only partial protection, and coatings of entirely different types may be applied over them.

Aluminium, magnesium, and zinc can be treated electrically in a suitable electrolyte to produce a corrosion-resistant oxide coating. The metal being treated is connected to the anode in the circuit, which provides the name anodizing for the process.

Corrosion of zinc can be substantially slowed by the production of chromium salts on its surface. The corrosion resistance of magnesium alloys can be increased by conversion. Treatment of both zinc and magnesium improves corrosion resistance but is used also to improve adhesion of paint.

Phosphate coatings, used mostly on steel, result from a chemical reaction of phosphoric acid with the metal to form a non-metallic coating that is essentially phosphate salts. The coating is produced by immersing small items or spraying large items with the phosphating solution.

A number of proprietary blackening processes, used mainly on steel, produce attractive black oxide coatings. Most of the processes involve the immersing of steel in a caustic soda solution heated to about 150°C (300°F) and made strongly oxidizing by the addition of nitrites or nitrates. Corrosion resistance is rather poor unless improved by application of oil, lacquer, or wax. As in the case of most of

the other chemical conversion procedures this procedure also finds use as a base for paint finishes.

2.4 MATERIALS IN SERVICE

2.4.1 Behaviour of materials in service

Materials have to operate and perform in widely varied environments and situations. The requirements of safety and reliability demand that the materials and components should perform well in their environments and situations without premature failure. There are a number of factors and processes which can cause the failure of materials. As premature failure of critical components can be disastrous in many situations apart from being a cause for lost production and bad reputation, it is essential to understand and control these causes of failure.

2.4.2 Conditions leading to defects and failures

Due to advances in technology and the understanding of materials and their design, and due to sophisticated inspection and testing methods, such as the non-destructive testing methods, metal failures occur only in an extremely low percentage of the millions of tons of metals fabricated every year. Those that do occur fall mainly into three categories. Operational failures can be caused by overload, wear, corrosion and stress corrosion, brittle fracture and metal fatigue. In the second category fall the failures due to improper design. In this it is necessary to consider whether sharp corners or high-stress areas exist in the design, has sufficient safety stress factor been considered and whether the material selected is suitable for particular application. The third type of failure is caused by thermal treatments such as forging, hardening, tempering and welding, and by surface cracks caused by the heat of grinding. These aspects and especially those related to operational or in-service conditions will be described here in more detail.

2.4.2.1 Corrosion

With the exception of some noble metals, all metals are subject to the deterioration caused by ordinary corrosion. Iron, for example, tends to revert back to its natural state of iron oxide. Other metals revert to sulphides and oxides or carbonates. Buildings, ships, machines and automobiles are all subject to attack by the environment. The corrosion that results often renders them useless and they have to be scrapped. Billions of dollars a year are lost as a result of corrosion. Corrosion can also cause dangerous conditions to prevail, such as on bridges, where the supporting structures have been eaten away, or in aircraft in which an insidious corrosion called intergranular corrosion can weaken the structural members of the aircraft and cause a sudden failure.

Corrosion in metals is the result of their desire to unite with oxygen in the atmosphere or in other environments to return to a more stable compound, usually called ore. Iron ore, for example, is in some cases simply iron rust. Corrosion may be classified by the two different processes by which it can take place; direct

oxidation corrosion, which usually happens at high temperature, and galvanic corrosion, which takes place at normal temperatures in the presence of moisture or an electrolyte. Direct oxidation corrosion is often seen in the scaling that takes place when a piece of metal is left in a furnace for a length of time. The black scale is actually a form of iron oxide, called magnetite (Fe_3O_4). Galvanic corrosion is essentially an electrochemical process that causes a deterioration of metals by a very slow but persistent action. In this process, part or all of the metal becomes transformed from the metallic state to the ionic state and often forms a chemical compound in the electrolyte. On the surface of some metals such as copper or aluminium, the corrosion product sometimes exists as a thin film that resists further corrosion. In other metals such as iron, the film of oxide that forms is so porous that it does not resist further corrosive action, and corrosion continues until the whole piece has been converted to the oxide.

It is familiarly known that atoms having positive or negative charges are called ions and these are formed either by accepting or donating electrons in the outermost orbit. Metallic atoms form positive ions while non-metals form negative ones. Ions having opposite charges can often combine to form compounds. An electrolyte is any solution that conducts electric current and contains negative or positive ions. Corrosion requires the presence of an electrolyte to allow metal ions to go into solution. The electrolyte may be fresh or salt water and acid or alkaline solutions of any concentration. Even a finger print on metal can form an electrolyte and produce corrosion. When corrosion of a metal occurs, positively charged atoms are released or detached from the solid surface and enter into solution as metallic ions while the corresponding negative charges in the form of electrons are left behind in the metal. The detached positive ions bear one or more positive charges. In the corrosion of iron, each iron atom releases two electrons and then becomes a ferrous iron carrying two positive charges. Two electrons must then pass through a conductor to the cathode area. The electrons reach the surface of the cathode material and neutralize positively charged hydrogen ions that have become attached to the cathode surface. Two of these ions will now become neutral atoms, and are released generally in the form of hydrogen gas. This release of the positively charged hydrogen ions leaves an accumulation and a concentration of OH negative ions that increases the alkalinity at the cathode.

When this process is taking place, it can be observed that hydrogen bubbles are forming at the cathode only. When cathodes and anodes are formed on a single piece of metal, their particular locations are determined by, for example, the lack of homogeneity in the metal, surface imperfections, stresses, inclusions in the metal, or any thing that can form a crevice such as a washer.

Corrosion can also take the form of erosion in which the protective film, usually an oxide film, is removed by a rapidly moving atmosphere or medium. Depolarization can also take place, for example, on the propellers of ships because of the movement through the water, which is the electrolyte. This causes an increased corrosion rate of the anodic steel ship's hull. Impellers of pumps are often corroded by this form of erosion corrosion in which metal ions are rapidly removed at the periphery of the impeller but are concentrated near the centre

where the velocity is lower. Another form of corrosion is intergranular corrosion. This takes place internally. Often the grain boundaries form anodes and the grains themselves form cathodes, causing a complete deterioration of the metal in which it simply crumbles when it fails. This often occurs in stainless steels in which chromium carbides precipitate at the grain boundaries. This lowers the chromium content adjacent to the grain boundaries, thus creating a galvanic cell. Differences in environment can cause a high concentration of oxygen ions. This is called cell concentration corrosion. Pitting corrosion is localized and results in small holes on the surface of a metal caused by a concentration cell at that point. When high stresses are applied to metals in a corrosive environment, cracking can also be accelerated in the form of stress corrosion failure. It is a very localized phenomenon and results in a cracking type of failure.

Cathodic protection is often used to protect steel ships hulls and buried steel pipelines. This is done by using zinc and magnesium sacrificial anodes that are bolted to the ship's hull or buried in the ground at intervals and electrically connected to the metal to be protected. In the case of the ship, the bronze propeller acts as a cathode, the steel hull as an anode and the sea water as an electrolyte. Severe corrosion can occur on the hull as a result of galvanic action. The sacrificial anodes are very near the anodic end of the galvanic series and have a large potential differences between both the steel hull of the ship and the bronze propeller. Both the hull and propeller become cathodic and consequently do not deteriorate. The zinc or magnesium anodes are replaced from time to time.

Selection of materials is of foremost importance. Even though a material may be normally resistant to corrosion, it may fail in a particular environment or if coupled with a more cathodic metal. Coatings are extensively used to prevent corrosion. There are different types of such coatings, for example; anodic coatings, cathodic coatings, organic and inorganic coatings, inhibitive coatings, etc.

2.4.2.2 Fatigue

When metal parts are subjected to repeated loading and unloading over prolonged periods they may fail at stresses far below their yield strength with no sign of macroscopic plastic deformation. This is called a fatigue failure. When designing machine parts that are subject to vibration or cyclic loads, fatigue strength may be more important than ultimate tensile or yield strength. Fatigue is a universal phenomenon observed in most solids. Cyclic loading leads to a continuous accumulation of damage which, as in the case of static fracture, eventually results in rupture. Fatigue limit, or endurance limit, is the maximum load that can be applied an infinite number of times without causing failure. But 10 million loading cycles are usually considered enough to establish fatigue limits. The number of cycles leading to fracture at a given stress is often referred to as the fatigue strength or endurance. This phenomenon of failure of a material when subjected to a number of varying stress cycles is known as fatigue since it was once thought that fracture occurred due to the metal weakening or becoming tired.

Failures caused by fatigue are found in many of the materials of industry. Some plastics and most metals are subject to fatigue in varying degrees as these are widely used in dynamically loaded structures and machines. It has been estimated that at least 75% of all machine and structure failures have been caused by some form of fatigue. Fatigue failure is caused by a crack that is initiated by a notch, bend, or scratch that continues to grow gradually as a result of stress reversals on the part. The crack growth continues until the cross-sectional area of the part is reduced sufficiently to weaken the part to the point of failure. In welding, even spatter on a sensitive surface such as a steel spring can initiate fatigue failure. Fatigue is greatly influenced by the kind of material, grain structure and the kind of loading. Some metals are more sensitive to sharp changes in section (notch sensitive) than others.

There are various types of fatigue failure. In the case of one-way bending load a small elliptically shaped fatigue crack usually starts at a surface flaw such as a scratch or tool mark. The crack tends to flatten out as it grows. It is caused by the stress at the base of the crack being lower because of the decrease in distance from the edge of the crack to the neutral axis. If a distinct stress raiser such as a notch is present, the stress at the base of the crack would be high, causing the crack to progress rapidly near the surface, and the crack tends to flatten out sooner. In a two-way bending load cracks start almost simultaneously at opposite surfaces when the surfaces are equally stressed. The cracks proceed toward the centre at similar rates and result in a fracture that is rather symmetrical.

In the early stages of fatigue testing, specimens will generally evolve an appreciable amount of heat. Later fissures develop at the surface eventually leading to failure. The surface of the specimen is a preferential seat of damage initiation. Corrosive effects may also assist in degradation of the structure at the surface. Corrosion is essentially a process of oxidation and under static conditions a protective oxide film is formed which tends to retard further corrosion attack. In the presence of cyclic stress the situation is quite different, since the partly protective oxide film is ruptured in every cycle allowing further attack. It is a rather simplified explanation that the microstructure at the surface of the metal is attacked by the corrosive environment causing an easier and more rapid initiation of cracks. One of the important aspects of corrosion fatigue is that a metal having a fatigue limit in air no longer possesses one in the corrosive environment and therefore fracture can occur at relatively very low stress levels.

In commercial alloys the technical fatigue limit generally lies between 0.3 and 0.5 of the ultimate tensile stress. The fatigue strength of metals can often be enhanced by treatments which render the surface more resistant to deformation. Fracture then tends to start at the interface between the hard surface layer and the softer core. Stress raisers, such as sharp notches, corners, key ways, rivet holes and scratches can lead to an appreciable lowering of the fatigue strength of metal components. Good surface finish and corrosion protection are desirable to enhance fatigue resistance. Fatigue is basically a low temperature problem and, at temperatures relatively high with respect to the melting point, fracture and hence specimen life are governed by creep.

Fractured surfaces of fatigued metals generally show a smooth and lustrous region due to the polishing effects arising from attrition at fissures. The remaining parts of the fracture surface, over which failure occurred through weakening of the specimen by the reduction of its load bearing cross-section by surface cracks and fissures, may look duller and coarser, as it is essentially caused by static fracture.

2.4.2.3 Wear

Wear may be defined as undesired removal of material from contacting surfaces by mechanical action. Excessive wear can be caused by continuous overload, but wear is ordinarily a slow process that is related to the friction between two surfaces. Rapid wear can often be attributed to lack of lubrication or the improper selection of material for the wear surface. Some wear is to be expected, however, and could be called normal wear. Wear is one of the most frequent causes of failure. We find normal wear in machine tooling such as carbide and high-speed tools that wear and have to be replaced or resharpened. Parts of automobiles ultimately wear until an overhaul is required. Machines are regularly inspected for worn parts, which when found are replaced; this is called preventive maintenance. Often normal wear cannot be prevented; it is simply accepted, but it can be kept to a minimum by the proper use of lubricants. Rapid wear can occur if the load distribution is concentrated in a small area because of the part design or shape. This can be altered by redesign to offer more wear surface. Speeds that are too high can increase friction considerably and cause rapid wear.

Metallic wear is a surface phenomenon, which is caused by the displacement and detachment of surface particles. All surfaces subjected to either rolling or sliding contact show some wear. In some severe cases the wear surface can become cold welded to the other surface. In fact, some metals are pressure welded together in machines, taking advantage of their tendency to be cold welded. This happens when tiny projections of metal make a direct contact on the other surface and produce friction and heat, causing them to be welded to the opposite surface if the material is soft. Metal is torn off if the material is brittle. Insufficient lubrication is usually the cause of this problem. High pressure lubricants are often used while pressing two parts together in order to prevent this sort of welding. Two steel parts such as a steel shaft and a steel bore in a gear or sprocket, if pressed together dry, will virtually always cease or weld and cause the two parts to be ruined for further use. In general, soft metals, when forced together, have a greater tendency to "cold weld" than harder metals. Two extremely hard metals even when dry will have very little tendency to weld together. For this reason, hardened steel bushings and hardened pins, are often used in earth moving machinery to avoid wear. Some soft metals when used together for bearing surfaces (for example, aluminium to aluminium) have a very great tendency to weld or cease. Among these metals are aluminium, copper and austenitic stainless steel.

Cast iron, when sliding on cast iron as is found in machine tools on the ways of lathes or milling machine tables, has less tendency than most metals to cease because the metal contains graphite flakes that provide some lubrication, although

additional lubrication is still necessary. As a general rule, however, it is not good practice to use the same metal for two bearing surfaces that are in contact. However, if a soft steel pin is used in a soft steel link or arm, it should have a sufficiently loose fit to avoid ceasing. In this application it is better practice to use a bronze bushing or other bearing material in the hole than a steel pin because the steel pin is harder than the bronze and when a heavy load is applied, the small projections of bronze are flattened instead of torn out. Also, the bronze will wear more than the steel and usually only the bushing will need replacing when a repair is needed.

Different types of wear include abrasive wear, erosive wear, corrosive wear and surface fatigue. In abrasive wear small particles are torn off the surfaces of the metal, creating friction. Friction involving abrasive wear is sometimes used or even required in a mechanism such as on the brakes of an automobile. The materials are designed to minimise wear with the greatest amount of friction in this case. Where friction is not desired, a lubricant is normally used to provide a barrier between the two surfaces. This can be done by heavy lubricating films or lighter boundary lubrication in which there is a residual film. Erosive wear is often found in areas that are subjected to a flow of particles or gases that impinge on the metal at high velocities. Sand blasting, which is sometimes used to clean parts, utilizes this principle. Corrosive wear takes place as a result of an acid, caustic, or other corrosive medium in contact with metal parts. When lubricants become contaminated with corrosive materials, pitting can occur in such areas as machine bearings. Surface fatigue is often found on roll or ball bearing or sleeve bearings where excessive side thrust has been applied to the bearing. It is seen as a fine crack or as small pieces falling out of the surface.

Various other methods, apart from lubrication, are used to limit the amount of wear in the part. One of the most commonly used methods is simply to harden the part. Also, the part can be surface hardened by diffusion of a material, such as carbon or chrome, into the surface of the part. Parts can also be metallized, hard faced, or heat treated. Other methods of limiting wear are electroplating (especially the use of hard industrial chromium) and anodizing of aluminium. Some nickel plate is used, as well as rhodium, which is very hard and has high heat resistance. The oxide coating that is formed by anodizing on certain metal such as magnesium, zinc, aluminium, and their alloys is very hard and wear resistant. These oxides are porous enough to form a base for paint or stain to give it further resistance to corrosion. Some of the types of diffusion surfacing are carburizing, carbo-nitriding, cyaniding, nitriding, chromizing, and siliconizing. Chromizing consists of the introduction of chromium into the surface layers of the base metal. This is sometimes done by the use of chromium powder and lead baths in which the part is immersed at a relatively high temperature. This, of course, produces a stainless steel on the surface of low carbon steel or an iron base metal, but it may also be applied to nonferrous material such as tungsten, molybdenum, cobalt, or nickel to improve corrosion and wear resistance. The fusion of silicon, which is called ihrigizing, consists of impregnating an iron base material with silicon. This also greatly increases wear resistance.

Hard facing is put on a metal by the use of several types of welding operations, and it is simply a hard type of metal alloy such as alloying cobalt and tungsten or tungsten carbide that produces an extremely hard surface that is very wear resistant. Metal spraying is used for the purpose of making hard wear resistant surfaces and for repairing worn surfaces.

2.4.2.4 Overload

Overload failures are usually attributed to faulty design, extra loads applied, or an unforeseen machine movement. Shock loads or loads applied above the design limit are quite often the cause of the breakdown of machinery. Although mechanical engineers always plan for a high safety factor in designs (for instance the 10 to 1 safety factor above the yield strength that is sometimes used in fasteners), the operators of machinery often tend to use machines above their design limit. Of course, this kind of overstress is due to operator error. Inadequate design can sometimes play a part in overload failures. Improper material selection in the design of the part or improper heat treatment can cause some failures when overload is a factor. Often a machinist or welder will select a metal bar or piece for a job based upon its ultimate tensile strength rather than upon its yield point. In effect this is a design error and can ultimately result in breakdown.

Basically there are only two modes or ways in which metals can fracture under single or monotonic loads. These two modes are shear and cleavage and they differ primarily in the way the basic metal crystal structure behaves under load. Almost all commercial solid metals are polycrystalline. Each individual crystal or grain is a structure composed of a very large number of atoms of the constituent elements. These atoms are arranged in cells within each crystal in a regular, repetitive three-dimensional pattern. Adjacent cells share the corner atoms and their positions are balanced by electrical forces of attraction and repulsion. Applied forces can cause distortion of the cells. Shear deformation represents a sliding action on planes of atoms in crystals. In a polycrystalline metal slight deformation causes no permanent change in shape, it is called elastic deformation. That is, the metal returns to its original size and shape, like a spring, after being unloaded. If a greater load is imposed, permanent or plastic deformation occurs because of irreversible slip between certain planes of atoms that make up the crystal structure. If the applied load or force is continued, the shear deformation causes tiny microvoids to form in the most highly stressed region. These tiny voids soon interconnect and form fracture surfaces. The cleavage mode of separation of the cell is different. In this case separation occurs suddenly between one face of the cell and the mating face of the adjacent cell without any deformation being present.

Fracture will originate whenever the local stress i.e. load per unit cross-sectional area, first exceeds the local strength. This location will vary depending upon the strength of the metal and the applied stress. When a shaft or similar shape is pulled by tensile force it becomes longer and narrower. For ductile metals the shear strength is the weak link and these metals fail through the shear mode. These metals fail when shear stress exceeds the shear strength. In the case of brittle metals, these fail because the tensile stress exceeds the tensile strength. Brittle metals always have a fracture that is perpendicular to the tensile stress and

little or no deformation because fracture takes place before the metal can deform plastically as ductile metals do.

When a cylinder is loaded in axial compression, a ductile metal becomes shorter and thicker. In short it bulges when squeezed by the compressive force and there is no fracture. A brittle metal in pure compression will fracture parallel to the length of the cylinder.

2.4.2.5 Brittle and ductile fracture

Fracture preceded by a significant amount of plastic deformation is known as ductile fracture, otherwise it is brittle fracture. Brittle fracture occurs when plastic flow is inhibited either by the effective locking of atomic dislocations by precipitates or elements or by the pre-existence or formation of cracks and imperfections acting as local stress raisers in the material. All materials can be embrittled if the temperature is lowered sufficiently. Glass, sealing wax, germanium, silicon and other materials though ductile at temperatures close to their melting point are brittle at ordinary temperatures. In most materials the brittle strength, defined as the maximum tensile stress withstood without the occurrence of brittle fracture, is low compared with the ideal strength the fault-free material would be expected to exhibit. The source of brittle fracture is therefore to be sought in the presence of structural defects.

As has already been mentioned brittle metals always have a fracture that is perpendicular to the tensile stress and have little or no deformation because fracture takes place before the metal can deform plastically. Thus a tensile fracture of a brittle metal has a fracture plane that is essentially straight across. It also usually has a characteristic bright sparkling appearance when freshly fractured.

The pattern of a break can often reveal how the failure was precipitated. For example, if the break was caused by a sudden shock load such as an explosion, there are usually chevron-shaped formations present that point to the origin of fracture. When a stress concentration is present, such as a weld on a structure that is subject to a sudden overload, the fracture is usually brittle across the entire break showing crystals, striations, and wave fronts. Brittle fractures are often intergranular (along the grain boundaries); this gives the fracture surface a rock candy appearance at high magnification. When grain boundaries are weakened by corrosion, hydrogen, heat damage, or impurities, the brittle fracture may be intergranular. Brittle failures can also be transgranular (through the grains); this is called cleavage.

Cleavage fracture is confined to certain crystallographic planes that are found in body centred cubic or hexagonal close-packed crystal structures. For the most part, metals having other crystalline unit structures do not fail by cleavage unless it is by stress corrosion cracking or by corrosion fatigue. Cleavage should normally have a flat, smooth surface; however, because metals are polycrystalline with the fracture path randomly oriented through the grains and because of certain imperfections, certain patterns are formed on the surface.

Small quantities of hydrogen have a great effect on the ductility of some metals. Hydrogen can get into steels when they are heated in an atmosphere or a material containing hydrogen, such as during pickling or cleaning operations, electroplating, cold working, welding in the presence of hydrogen-bearing compounds, or the steel-making process itself. There is a noticeable embrittling effect in steels containing hydrogen. This can be detected in tensile tests and seen in the plastic region of the stress- strain diagram showing a loss in ductility. Monatomic hydrogen is produced by most pickling or plating operations at the metal-liquid interface, and it seems that single hydrogen atoms can readily diffuse into the metal. Preventive measures can be taken to reduce this accumulation of hydrogen gas on the surface of the metal.

A frequent source of hydrogen embrittlement is found in the welding process. Welding operations in which hydrogen-bearing compounds such as oil, grease, paint, or water are present, are capable of infusing hydrogen into the molten metal, thus embrittling the weld zone. Special shielding methods are often used that help to reduce the amount of hydrogen absorption. One effective method of removing hydrogen is a 'baking' treatment in which the part, or in some cases the welding rod, is heated for long periods of time at temperatures of 121 to 204^{o}C. This treatment promotes the escape of hydrogen from the metal and restores the ductility.

Stress raisers such as notches on the surface of a material have a weakening effect and cause embrittlement. A classical example is provided by the internal notches due to graphite flakes in cast irons. The flakes embrittle the irons in tension. Therefore in structural applications cast irons are most usefully employed under compressive loads. Their brittle strength and toughness can, however, be increased appreciably if the graphite is allowed to form in spheroidal rather than flaky form. This can be done by alloying the melt, for example, with magnesium.

2.5 NON-METALLIC MATERIALS

2.5.1 Ceramics

Ceramics offer unique properties as engineering materials, notably exceptionally high hardness and resistance to abrasion and corrosion as well as high temperature properties considerably superior to those of any metals. Their main limitations are a certain absence of ductility, they are intrinsically brittle materials and also susceptible to thermal shock which can limit their maximum service temperature on applications involving thermal cycling. Resistance to thermal shock is directly dependent on a low coefficient of thermal expansion and high thermal conductivity, which properties differ appreciably between different ceramic materials.

The problems relating to thermal and mechanical shock can be reduced by suitable design of components, e.g. the use of thin sections and the reduction of mechanical restraint to a minimum. The use of ceramics as engineering materials represents a new and necessary challenge to designers to make the most of their exceptional properties, whilst reducing the possibilities of damage through mechanical of thermal shock to a minimum by intelligent design.

The fabrication of ceramics does not set particular problems since they can be formed by traditional techniques such as slip casting wet pressing and extrusion, and by such modern methods as injection moulding, isostatic apressing, tape casting and dry pressing.

Ceramics which can be classified (or are usable or potentially usable) as engineering materials currently embrace:

(i) alumina
(ii) beryllia (beryllium oxide) and boron nitride
(iii) porcelain (aluminium silicates)
(iv) steatite and forsterite (magnesium silicates)
(v) silicon nitride and silicon carbide
(vi) titanium diboride
(vii) vitreous carbon
(viii) partially stabilised zirconia (PSZ)
(ix) titanium carbonate
(x) lead titanate circonate (PZT).

Of these, porcelain ceramics are by far the most widely used and developed throughout industry, the main applications being in the field of electrical insulation where they are used as large insulators to carry high voltages of national grid networks and are familiar to most people.

Alumina ceramics on the other hand, although not having the volume of usage compared with porcelain, are probably the most technically developed of the new ceramic materials. Their high mechanical properties, ease of fabrication and relative cheapness have led to a rapid increase in their use over the last three decades. The main competitors of alumina ceramics are an even newer brand of ceramic materials, namely silicon nitride and silicon carbide. Although the technology of silicon nitride is still in its infancy, silicon carbide has been used for many years as an abrasive medium but has yet to establish itself in the broader engineering field.

Ceramics are finding an increasing use in the fabrication of electronic components, engineering components, medicine and dentistry and jewelry.

2.5.2 Cermets

The use of ceramic-coated metals and ceramic-metal combinations has now assumed significant proportions, particularly in the fields of practical nuclear physics (e.g. parts for nuclear reactors) and jet engine manufacture. Metal ceramic combinations are of two types a ceramic coating on the metal, or a chemical and mechanical combination of metals and ceramics in a cermet material. Both are essentially attempts to produce satisfactory high-temperature materials, either with reduced costs and better availability or with an over-all performance superior to existing metal or ceramic materials on their own. Broadly speaking the mechanical properties of these two types of materials represent extremes. Metals have high tensile strength and shock resistance, but lose these properties rapidly with increasing temperature. Ceramics of the refractory kind have extremely high melting points and excellent general stability, but are low in tensile strength and both mechanical and thermal shock resistance. The demand for materials

combining the favourable features of both metals and ceramics is increasing; hence the development of combinations of ceramics with metals over the past few years.

Consider first the ceramic material applied as a coating on metals. Such coatings can be used to give the finished component a chemical inertness at both high and low temperatures, whilst retaining good thermal shock resistance and the desirable tensile strength figure of the metal. Such coatings, largely by their direct insulting value, coupled with low porosity, reduce oxidation of the metal surface and suppress inter-granular corrosion up to much higher temperatures. Thus a low alloy steel, suitably coated, can give a satisfactory performance at high-service temperatures comparable to that realized by a special high-duty (high alloy) steel. Saving in both material and fabrication costs can be considerable as a result.

One of the main difficulties is how to get the ceramic coating on the metal surface. Until comparatively recently the favoured method was to use an enameling frit comprised chiefly of alumina and silica, with the addition of certain metallic oxides. Gradually, however, the tendency has been to increase the metallic content of the coating mixtures until they approximate more closely to a true cermet mixture. This, in its turn, has led to applying the coating by flame spraying.

Normally cermets are formed by techniques similar to those employed in powder metallurgy. The ceramic content usually comprises refractory oxides, carbides or nitrides whilst the metal powder component is usually chromium, nickel, molybdenum or titanium. The resulting properties are different from those of either of the separate constituents. A number have particularly high melting points, best realized in an open flame.

The thickness of ceramic coating required on jet, piston and rocket engine components is usually quite small and may be of the order of one-thousandth of an inch. Where an extremely high-duty component is required a high-temperature alloy may be used in the first place with its normal service temperature extended by a coating of high melting point refractory material. Often the fusing temperature required to fix a frit coating is above that which the metal itself can withstand without undergoing inter-granular corrosion or similar physical change with resulting loss of properties. Additionally, special insulted furnaces are required in any case to achieve such high temperatures and the part or assembly being treated may be of such a size or shape to make furnace loading impractical. In such instances flame spraying the ceramic coating has obvious possibilities since the temperature of the metal surface is not necessarily raised to anything like the melting point of the ceramic or cermet and also the coating can be applied in the open.

The type of spray gun used is similar to that used for conventional metal spraying. Nickel magnesia cermet is prepared from nickel and magnesium oxide, intimately mixed, sintered and ground to powder. The powder is placed in a metal container attached to the flame-spraying gun and piped through a tube to the hot torch nozzle by nitrogen gas under pressure. The heating flame is oxyacetylene, with a temperature of about 3040°C (5500°F), or appreciably above the melting point of the cermet. The cermet powder is thus liquefied as it is blown through the flame and ejected in the form of a

thick spray. It cools quite rapidly on contacting the cool metal surface and solidifies in the form of an adherent refractory coating.

Nickel magnesia cermet has been applied successfully to stainless steels, high duty alloy steels, Inconel, etc. by flame spraying, and to both simple and complicated shapes. One of the most exacting jobs has been the application of uniform, thin coatings on corrugated members with thin walls such as afterburner liners for jet engines. Warpage under excessive heating was a common fault with furnace fusion of ceramic coatings, which flame spraying seems largely to have obviated. The main problem in this particular case appears to have been cleaning the corrugated liners before treatment. Sandblasting or similar abrasive cleaning could not be employed on account of the thin metal gauge.

The types of refractory coatings used for the protection of exhaust system components on jet and piston engines are normally metallic oxides and, therefore, extremely resistance to oxidation and corrosive attack. A number, also, have fluxing properties so that it has proved practical to are weld through the coatings. Thus relatively large structures have been prefabricated in sections, ceramic coated and then assembled by welding with perfectly satisfactory resulting and an appreciable saving in time and trouble. Ceramic materials with good thermal shock properties are required in such cases when the coating disrupted at the weld zone will blend smoothly into the weld without spalling.

Practical performance figures and possible limitations are a little difficult to evaluate at the present stage, particularly with regard to flame-sprayed coatings. In general, however, nickel-magnesia cermet coatings are reckoned to all a further 150° to the range of operating temperatures of existing high duty alloys. It should be emphasized, however, that the value of ceramic coatings on metals is not confined to ultra-high temperature duties. Their value is also considerable as a means of retarding oxidation, corrosion, carbon absorption, etc. of metals at more moderate working temperatures, but under adverse conditions.

2.5.3 Composites

A composite is a material in which a stronger, sometimes fibrous material is usually combined with another to reinforce or strengthen the resultant mass. The needs of the aerospace industry led to the development and acceptance of composite material. Low weight, high strength and great rigidity were of paramount interest of military aviation. These same qualities are also in demand in many non-military applications.

The most common forms of composite are based on a plastic matrix. The fibrous reinforcing material may be in sheet form, as in thermoset plastic laminates; filament form, woven or random, as in glass reinforced plastics; or short fibre form as in filled or reinforced thermoplastics. These materials are well established and widely available.

In the case of thermoset laminate composites, phenolic, melamine and epoxide are the main resin systems used, with paper, cotton fabric, glass fabric and asbestos as the main alternative reinforcing materials.

In the case of glass reinforced plastics (GRP) the principal resin systems used are polyester and epoxide with silicones and polyimides for more specialized applications i.e. again thermoset plastics. Reinforcement takes the form of glass cloth, rovings, chopped strand mat, or a mixture of these disposed through the lay up. The finished (cured) material is again basically a laminate, but distinguished from those described as Laminated Plastics by the common employment of glass fibre reinforcement. Even this is not exclusive as carbon fibre is an alternative form of reinforcement (CFRP), and other reinforcement materials may be used, e.g. synthetic fabrics. Such composites may be rendered in flat sheet form like laminated plastics (e.g. for printed circuit boards), although they are more usually applied to specified forms by laying up, dough moulding, sheet forming or filament winding.

In the case of reinforced theremoplastics used for injection moulding, considerable improvements in mechanical properties can be realized by 'loading' with short fibres of glass, asbestos, or other high strength filaments. Glass fibre is the most common reinforcement, the resulting thermoplastic being referred to as 'glass filled'. Asbestos filled thermoplastics have rather more specialized application, whilst carbon fibre 'filling' is a more recent, and as yet relatively undeveloped, alternative applied to virtually any thermoplastic, but is not necessarily commercially viable. The main application of glass filling is to acetals and nylons.

Fibrous reinforcement can be applied to matrices other than plastic notably ceramics, cement and concrete, and metals. The reinforcement material can be fibrous glass, asbestos, or high modulus filaments such as alumina, carbon boron fibre, silicon carbide or silica nitride 'whishers', etc., well as metallic filaments and whiskers. Notably, too, some high strength organic polymer fibres have been developed as reinforcement materials. There is also the possibility of producing aligned composites in a continuous casting process, e.g. a nickel aluminium eutectic melt yielding directionally oriented aluminium nickelide fibres in a pure aluminium matrix. Equally carbon fibre or similar filament reinforcement can be oriented in a metal composite to produce optimum stress distribution.

Ceramic and metal composites have remained relatively undeveloped as general engineering and constructional materials, largely on account of high cost. There are, however, numerous applications of 'filled' and 'laminated' metal forms which qualify as composites under the general description.

Cement and concrete composites are more readily, and cheaply, realized by simple premixing or lay-up techniques. The value of asbestos for strengthening cement has, in fact, been known and explored for a considerably number of years. More recently the addition of small quantities of nylon or polypropylene fibres has been found to reduce the inherent brittleness of cement mortars, with obvious advantages, and this has led to considerable further research in the field of organic fibrous reinforcement of cement itself as an alternative, or supplement, to metallic reinforcement.

Basically, the addition of organic polymetric reinforcement to concrete produces a significant increase in impact resistance of the cement matrix with little or no effect on tensile strength. A further virtue is that this improved impact resistance is not affected by ageing.

To improve the other mechanical properties of the cement matrix a high modulus fibre reinforcement can be used, such as asbestos, glass fibre or carbon fibre, as an alternative (or supplement) to conventional metallic reinforcement. Glass fibre composites show improve rupture strength, but have little or no effect on impact strength. Asbestos and carbon fibre improve rupture strength, but have little or no effect on impact strength. Glass fibre can be considered a low modulus, high strength reinforcement. Asbestos and carbon fibre are high modulus, high strength reinforcements. This largely explains the difference in the behaviour of composites with these inorganic reinforcements.

2.5.4 Concrete

Concrete is a mixture of stone and sand held together by a hardened paste of hydraulic cement and water. When the ingredients are thoroughly mixed they make a plastic mass which can be cast or moulded into a predetermined size and shape. When the cement paste hardens the concrete becomes very hard like a rock. It has great durability and has the ability to carry high loads especially in compression.

The required strength and properties of concrete can be obtained by careful selection of its ingredients, correct grading of ingredients, accurate water additions and adopting a good workmanship in mixing, transportation, placing, compaction, finishing, and curing of concrete in the construction work.

The main ingredients of concrete are cement, coarse aggregate (i.e. screenings, gravel, etc.), fine aggregate (i.e. sand), chemical admixtures (if necessary) and fibrous materials (as necessary). Aggregates in concrete constitute by far the bulk of the mass. Acceptable concretes usually have proportions within the following ranges (by volume):

Water	15% to 20%
Cement	7% to 17%
Aggregate (coarse and fine)	78% to 63%
Paste (water + cement)	22% to 37%

Typical characteristics which are desirable to be achieved in the body of a concrete mix include adequate compressive strength, uniformity of mixing, freedom from internal defects such as voids and cracks, high modulus of elasticity and dynamic poisson's ratio and correct positioning of reinforcing steel bars, freedom of reinforcing bars from corrosion, correct positioning of pipes in the concrete structures, uniformity of distribution of fibres in the fibre concrete, freedom from any foreign inclusions, uniformity of thickness and grouting ducts for post tensioned concrete and adequacy of covering depth over the reinforcements.

3. THE TECHNOLOGY OF NDT METHODS

Management personnel need a knowledge of the technical aspects of the NDT methods to an extent that they can appreciate their potential applications in their particular industries. This will allow them to communicate and interact in a better way with their own quality control personnel on the one hand and with the third party inspection agencies on the other. It will also help them in reaching a decision

as to which NDT techniques are most frequently needed by their organizations and for which investment in equipment and manpower would be fully justified for creating an in-house NDT set-up while which of the techniques are only sparingly needed so that hiring of the services of commercial NDT companies may be more beneficial. It is with this in view that this section of the book has been arranged. It gives greater details of the basic and more commonly used methods of NDT, namely, visual testing (VT), liquid penetrant testing (PT), magnetic particle testing (MT), eddy current testing (ET), rdiographic testing (RT) and ultrasonic testing (UT). Each of these methods is described under the headings of basic principles, equipment and recommended procedure, typical applications, range and limitations. The other methods are described only briefly just to give the manager an idea as to what additional methods are available with their specialized applications so that he can call upon them whenever a particular situation demands. To this latter class of methods for specialized applications belong acoustic emission, thermal and infrared methods, microwave testing, computer aided tomography, strain gauging, leak testing, radioisotope gauges, non-destructive analytical methods and some others. A brief description of most of these methods has been included.

3.1 VISUAL TESTING (VT)

Visual testing is the first NDT method that should be considered before applying more sophisticated and expensive methods. In this method direct visual and optically aided inspection is applied to the surface of object to detect flaws and anomalies. If significant flaws are detected during visual inspection then the part being inspected can be rejected on that basis. There is then hardly any need or justification for applying the other NDT methods.

3.1.1 Tools for visual inspection

The human eye is the most frequently used tool for visual inspection. It can be aided by lenses and magnifiers. At places where direct vision is not possible boroscopes can be used. The images can be observed under visible light or ultraviolet light may be used for fluorescent materials. Video and film cameras have also been employed for remote visual inspection. In fact liquid penetrant testing and magnetic particle testing are only more advanced forms of visual inspection.

3.1.2 Applications of visual inspection

Visual inspection can be applied to all sorts of materials for the detection of surface cracks, voids, pores, inclusions and for the assessment of surface roughness. It can be applied for metrology and dimensional measurements using mechanical gauges. Process control applications of visual inspection include both on-line and off-line monitoring control. As mentioned earlier it can be applied to all sorts of materials such as metallic and non-metallic, ferromagnetic and non-magnetic, conductors and non conductors, machined parts, components, assemblies and systems. However, the application of the technique is limited by the visual access which is needed and the specialized aids which are usually required. The sensitivity of the method depends upon the degree of magnification that may be achievable. For accurate flaw discrimination, detection and measurement, the information obtained by visual inspection may need to be supplemented by other NDT methods.

3.2 LIQUID PENETRANT TESTING (PT)

This is a method which can be employed for the detection of open-to-surface discontinuities in any industrial product which is made from a non-porous material. In this method a liquid penetrant is applied to the surface of the product for a certain predetermined time after which the excess penetrant is removed from the surface. The surface is then dried and a developer is applied to it. The penetrant which remains in the discontinuity is absorbed by the developer to indicate the presence as well as the location, size and nature of the discontinuity. The process is illustrated in Figure 3.1.

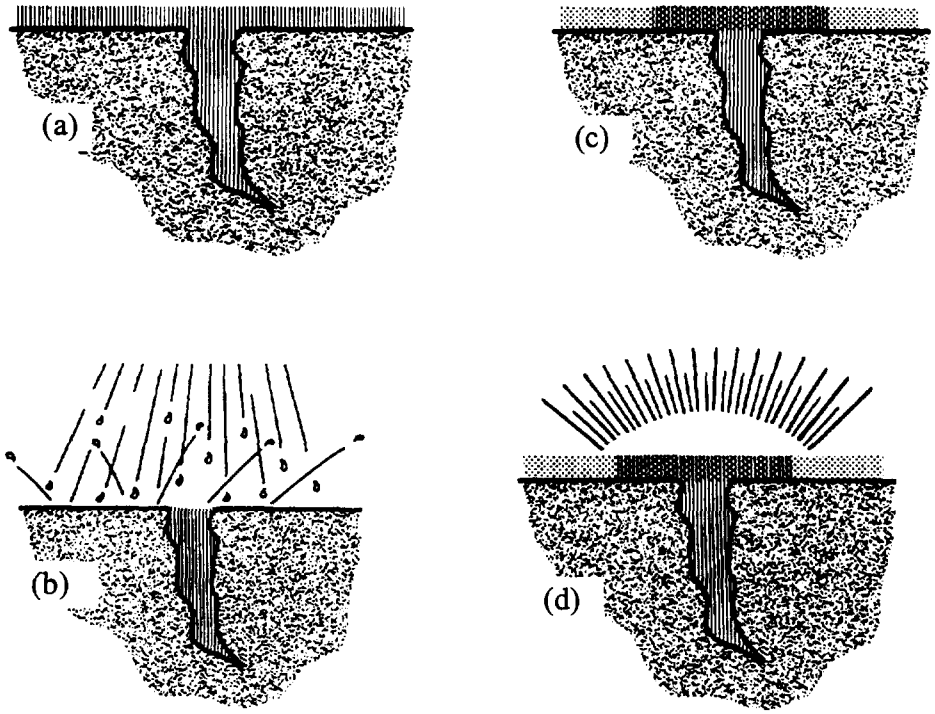


Figure 3.1 : Four stages of liquid penetrant process.

(a) Penetrant application and seepage into the discontinuity.
(b) Removal of excess penetrant.
(c) Application of developer.
(d) Inspection for the presence of discontinuities.

3.2.1 General procedure for liquid penetrant inspection

(a) Cleaning the surface to be examined

There should be no material such as plating, or coatings of oxide or loose dirt coveri(b) e surface. This is to prevent false indications and to expose hidden discontinuities to the penetrant. Solid contamin(d) such as carbon, engine varnish, paints and similar materials should be removed by vapour blast, chemical dip or other acceptable methods . Methods such as shot blasting, emery cloth, wire brushing or metal scrapping should not be used, especially for soft materials, since

these cleaning methods will cover up defects by cold working the surface. Contamination can occur due to the presence of lubricants, protective oils, metal dust polymerization, oxidation, carbonaceous deposits, protective paints, etc. Various solvents have been developed by different companies to remove them. Contamination due to inorganic corrosion products, heat treatment scale, operationally formed refractory oxides, etc. is conveniently removed by abrasive blasting with glass beads, etc. combined with a chemical cleaning. Whichever method is employed the use of trichlorethylene vapour degreasing as a final stage is strongly recommended.

(b) Drying the surface

If, for any reason, separations are filled with liquid, they will prevent entry of penetrant, hence drying is an essential operation . It should be realized that although the surface may seem dry, separations may still be filled with liquid. With "dismountable cracks" used to evaluate penetrants, it is remarkable how long a liquid can stay in a small separation after the outer surface has become dry. The lesson is that improper drying may be worse than no cleaning, because the remaining solvent may present a barrier to the penetrant too. If penetrant liquid does reach into the separation, it will be diluted by the solvent, and this also makes the treatment less effective.

(c) Application of penetrant

The penetrant is applied with the help of a brush or by spray or by dipping the test piece into a bath of penetrant. After this a certain residence time or 'dwell time' is allowed for the penetrant to seep into discontinuities. The residence time varies with the temperature, the type of penetrant, the nature of the discontinuity and the material of the test specimen. It usually varies between 5 and 30 minutes. In special cases it may be as long as one hour.

(d) Removal of superfluous penetrant

The excess penetrant on the surface should be removed to obtain optimum contrast and to prevent misleading indications. The appropriate remover is usually recommended by the manufacturer of the penetrant. Some penetrants are water washable while others need application of an emulsifier before they can be removed with water. The removal method is to use a sponge or water spray. There are special penetrant removers which are essentially solvents.

It is most important that removal of the penetrant is restricted to the surface and that no penetrant is washed out of the flaws which can easily happen when the cleaning is too rigorous. When the surface is smooth washing can be less intensive than for rough surfaces; in the latter case there is a definite risk that penetrant may be washed out of small imperfections.

A general criterion for the removal operation is that it must be fast and should be prolonged long enough to make the surface almost clean. It is better to leave small traces of penetrant on the surface than to carry out excessive cleaning. When

removing fluorescent penetrants, the effect of the treatment should preferably be watched under black light.

(e) Drying the surface

The surface can be dried with a dry cloth or an air blower. Drying is generally needed to prepare the surface for the application of a powder developer, which would otherwise clot at wet places. It also decreases the adverse effect of insufficiently removed traces of penetrant. Here again excess should be avoided. Penetrant liquid left in flaws should not be allowed to dry, and this can happen when hot air is used for drying.

(f) Application of developer

Developers are usually of two types namely dry and wet developer. Dry developer consists of a dry, light coloured powdery material. It is applied to the surface after removal of excess penetrant and drying of the part. It can be applied either by immersing the parts in a tank containing powder, or by brushing it on with a paint brush (usually not a desirable technique) or by blowing the powder onto the surface of the part.

Wet developer consists of a powdered material suspended in a suitable liquid such as water or a volatile solvent. It is applied to the parts immediately following the water washing operation.

Developers should be such that they provide a white coating that contrasts with the coloured dye penetrant, and draw the penetrant from the discontinuities to the surface of the developer film, thus revealing defects.

The dry developers are applied generally with fluorescent penetrants. They are applied just prior to the visual inspection process. The wet developers are also used in connection with fluorescent penetrants. They are applied after the washing operation and before the drying operation. The solvent based developers are generally used with the visible dye-penetrants. They are applied after cleaning off extra penetrant. A short time should be allowed for development of indications after the developer has been applied. This time should be approximately one half that allowed for penetration. Developer coating is removed after inspection by water stream, spray nozzle, brush, etc. The powder concentration of the liquid developer should be carefully controlled to obtain the required thin and uniform layer over the surface.

(g) Observation and interpretation of indications

An indication in the developer will become visible after a certain lapse of time. Because all penetrant inspection methods rely upon the seeing of an indication by the inspector, the lighting provided for this visual examination is extremely important. For best results, inspection for fluorescent indications should be done in a darkened area using black light. For the interpretation of indications, it is very important to observe their characteristics at the very moment they appear. As soon

as the flaws have bled out the indications may run to larger spots, depending on size and depth, and at this stage it is difficult to derive characteristic information from a flaw.

The extent to which observation of developing indications can be realized in practice depends largely on the size and complexity of the surface to be examined as well as on the number of components to be tested. A brief guide to the penetrant indications is given here. A crack usually shows up as a continuous line of penetrant indication. A cold shut on the surface of a casting also appears as a continuous line, generally a relatively narrow one. A forging lap may also cause a continuous line of penetrant indication. Rounded areas of penetrant indication signify gas holes or pin holes in castings.

Deep crater cracks in welds frequently show up as rounded indications. Penetrant indications in the form of small dots result from a porous condition. These may denote small pin holes or excessively coarse grains in castings or may be caused by a shrinkage cavity. Sometimes a large area presents a diffused appearance. With fluorescent penetrants, the whole surface may glow feebly. With dye penetrants, the background may be pink instead of white. This diffused condition may result from very fine, widespread porosity, such as microshrinkage in magnesium. Depth of defects will be indicated by richness of colour and speed of bleed out. The time required for an indication to develop is inversely proportional to the volume of the discontinuity.

3.2.2 Penetrant processes and equipment

Penetrants are classified depending on whether the dye fluoresces under black light or is highly contrasting under white light. A second major division of the penetrants is determined by the manner is which they can be removed from the surface. Some penetrants are water washable and can be removed from the surface by washing with ordinary tap water. Other penetrants are removed with special solvents. Some penetrants are not in themselves water washable but can be made so by applying an emulsifier as an extra step after penetration is completed. During a short emulsification period this emulsifier blends with the excess penetrant on the surface of the part after which the mixture is easily removed with a water spray.

The fluorescent penetrant water washable penetrant process uses this method. The fluorescent method is used for greater visibility; can be easily washed with water; is good for quantities of small parts; is good on rough surfaces; is good in keyways and threads; is high speed, economical of time and good for a wide range of defects.

The post emulsification fluorescent process has fluorescence for greater visibility; has highest sensitivity for very fine defects; can show wide shallow defects; is easily washed with water after emulsification; has a short penetration time; high production; especially satisfactory for chromate surfaces.

The water emulsifiable visible penetrant process has greater portability; requires no black light; can be used on suspected local areas of large parts; aids in rework or repair; can be used on parts where water is not available; can be used where parts

are to be repaired in ordinary light; best of all techniques on contaminated defects; sensitive to residual acidity or alkalinity; high sensitivity to very fine defects.

Fluorescent materials generally respond most actively to radiant energy of a wavelength of approximately 3650A. This is just outside the visible range on the blue or violet side but not sufficiently far removed to be in the chemically active or ultraviolet range : this is "black light". Four possible sources of black light are incandescent lamps, metallic or carbon arcs, tubular "BL" fluorescent lamps and enclosed mercury vapour arc lamps. Mercury vapour arc lamps are generally used. One of the advantages of this is that its light output can be controlled by design and manufacturing. At medium pressures (from 1 to 10 atmospheres) the light output is about evenly distributed between the visible, black light and hard ultraviolet ranges. These medium pressure lamps are ordinarily used for inspection purposes. A red purple glass is used to filter the light not desired. Factors such as the nature of inspected surface, extraneous white light entering the booth, the amount and location of fluorescent materials near the inspector and the speed with which inspection is to be carried out have an effect on the black light intensity necessary at the inspected surface. The light level, once it is set for a practical job, should be maintained. Good eyesight is also a requisite.

3.2.3 Areas of application of liquid penetrants

Liquid penetrants can be used for the inspection of all types of materials such as ferrous and non-ferrous, conductors and non-conductors, magnetic and non-magnetic and all sorts of alloys and plastics. Most common applications are in castings, forgings and welding.

3.2.4 Range and limitations of liquid penetrants

All imperfections which have an opening to the surface are detectable no matter what their orientation be. Sub-surface defects which are not open to the surface will not show up and consequently will not interfere with the interpretation. No indications are produced as a consequence of differences in permeability (a weld in dissimilar steels, transition zones, etc.). There is no risk of surface damage which may occur, for example, during careless magnetization with prods in the current flow method. The equipment is also low cost.

Flaws may remain undetected by penetrant inspection if magnetic particle testing has been previously used, because the residual iron oxide may fill or bridge the defect. Similarly fluorescent penetrant will often fail to show discontinuities previously found by dye-penetrant because the dye reduces or even kills fluorescence. Reinspection should be done with the same method. Surface condition may affect the indications. Surface openings may be closed due to dirt, scale, lubrication or polishing. Rough or porous areas may retain penetrant producing irrelevant indications. Deposits on the surface may dilute the penetrant, thus reducing its effectiveness.

If all the surface penetrant is not completely removed in the washing or rinse operation following the penetration time, the unremoved penetrant will be visible.

Such parts should be completely reprocessed. Degreasing is recommended. Another condition which may create false indications is where parts are press fitted to each other. The penetrant from the fit may bleed out and mask the true defect. Some of the precautions necessary for liquid penetrant inspection are briefly summarized here. Only one process should be used. Change of process is not advisable for reinspection. Contamination leads to a loss of test sensitivity and reliability. Contamination of water with penetrants should be avoided. Wet developer bath should be at the recommended concentration. The temperature should not exceed certain limits depending on materials used. The penetrant should not be heated. Avoid contact of penetrant with skin by wearing gloves. Keep penetrants off clothes. Check for traces of fluorescent penetrant on skin and clothes and inside gloves by examining under black light. Excessive amounts of dry penetrants should not be inhaled. Improperly arranged black lights may cause some eye fatigue. The materials used with visible penetrant process are flammable and should not be stored or used near heat or fire. Do not smoke while using them.

3.3 MAGNETIC PARTICLE TESTING

Magnetic particle testing is used for the testing of materials which can be easily magnetized. This method is capable of detecting open-to-surface and just below-the-surface flaws. In this method the test specimen is first magnetized either by using a permanent magnet or an electric current through or around the specimen. The magnetic field thus introduced into the specimen is composed of magnetic lines of force. Whenever there is a flaw which interrupts the flow of magnetic lines of force, some of these lines must exit and re-enter the specimen. These points of exit and re-entry form opposite magnetic poles and whenever minute magnetic particles are sprinkled onto the surface of the specimen, these particles are attracted by these magnetic poles to create a visual indication approximating the size and shape of the flaw. Figure 3.2 (a, b) illustrates the basic principle of this method.

3.3.1 Methods of magnetization

Electric currents are used to create or induce magnetic fields in magnetic materials. Several types of magnetization are in use for magnetic particle inspection. Some of the types are DC magnetization, half wave rectified current magnetization and AC magnetic particle inspection.

Direct current obtained from storage batteries was first believed to be the most desirable current to use, since it penetrates more deeply into test specimens than any other current. The big disadvantage of the current obtained from storage batteries is that there is a specific limit to the magnitude and duration of current, which can be drawn from the battery before recharging. Battery maintenance is costly and can become a source of trouble. Battery current can be replaced by the current obtained through dry plate rectifiers from AC power lines. This has the advantage of permitting an almost unlimited supply of DC.

Half wave rectified current is the most effective current to use for detection of surface and sub-surface defects using dry magnetic particles. It gives mobility to magnetic particles and aids in the formation of indications.

Alternating current is also used for detection of surface cracks like fatigue cracks. AC inspection units should be equipped with proper current controls. An advantage of using AC is that the parts being inspected with this current can be easily demagnetized.

Some of the commonly used methods of magnetizing the test specimens of different configurations are given below:

(a) Circular magnetization

Electric current passing through any straight conductor such as wire or bar creates a circular magnetic field around that conductor (Figure 3.3).

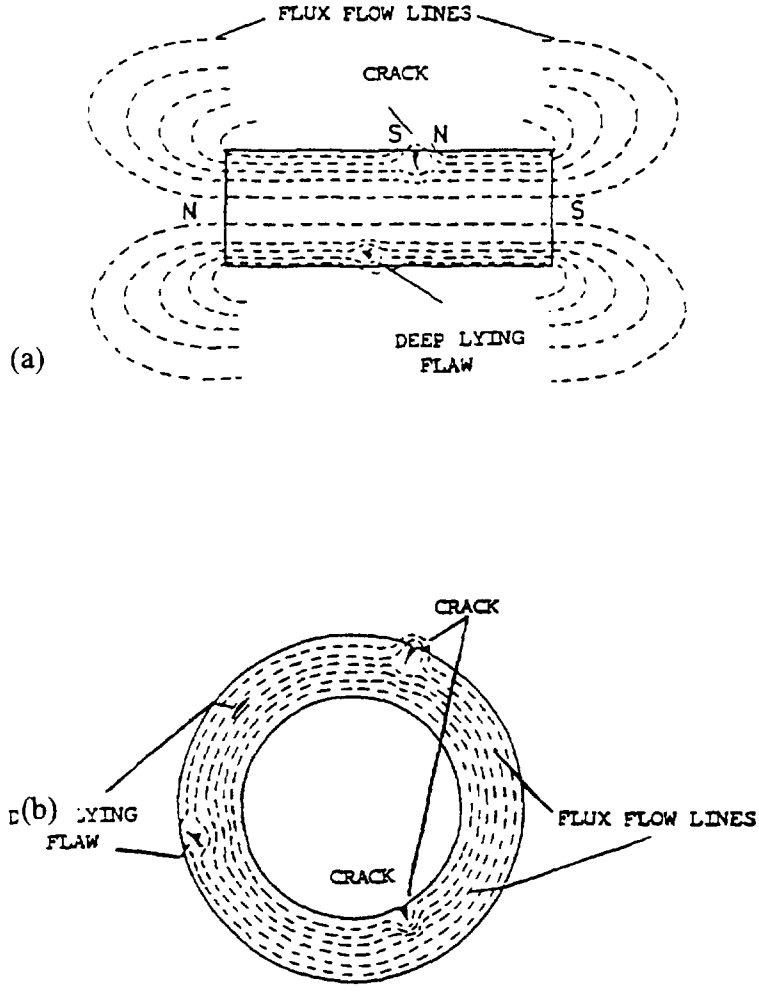


Figure 3.2.

(a) The effect of defects on the flux flow.

(b) The effect of defects on the flux flow in a magnetized ring.

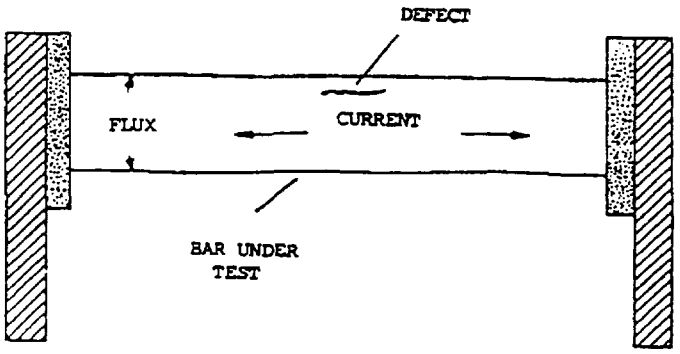


Figure 3.3 : Flux flow in a bar carrying current.

For inspection of axial cracks in a solid or hollow part, the part can be magnetized circularly. For a solid part the current is passed through the test piece and a circular field is developed inside and around the piece. In the case of hollow or tube like objects, a central conductor is used to carry the magnetizing current. The central conductor is always a copper rod. The conductor is placed inside the hollow piece and current is then applied to it. This induces a circular magnetic field on the inside and outside surface of the hollow piece as shown in Figure 3.4.

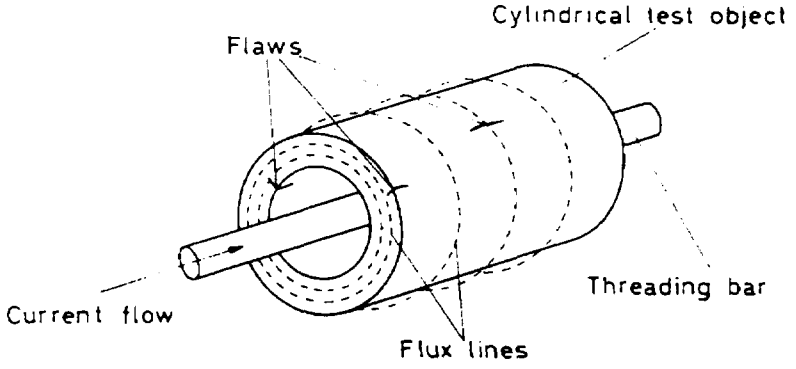


Figure 3.4 : Flux flow in cylindrical specimens using threading bar.

(b) Longitudinal magnetization

Parts can be magnetized longitudinally using a permanent magnet (Figure 3.5) or by using an electromagnet (Figure 3.6). Parts can also be magnetized longitudinally by the application of electric current in a coil. When electric current is passed through a coil of several turns, a magnetic field is established lengthwise or longitudinally within the coil. The nature and direction of this field is the result of the field around the conductor which forms due to the number of turns in the current carrying coil. A crack at right angles or tangential to this field can be revealed. Longitudinal magnetization may be achieved by surrounding the test specimen with helical coils and passing current through them (Figure 3.7).

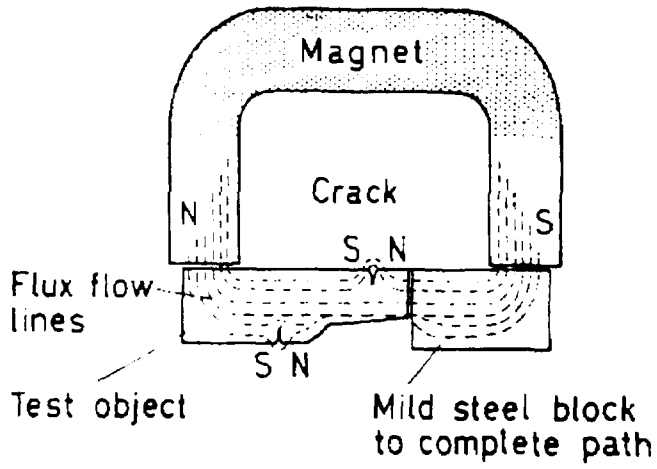


Figure 3.5 : Use of permanent magnet.

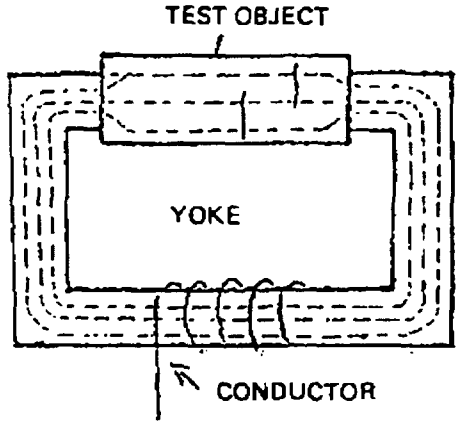


Figure 3.6 : Electromagnet.

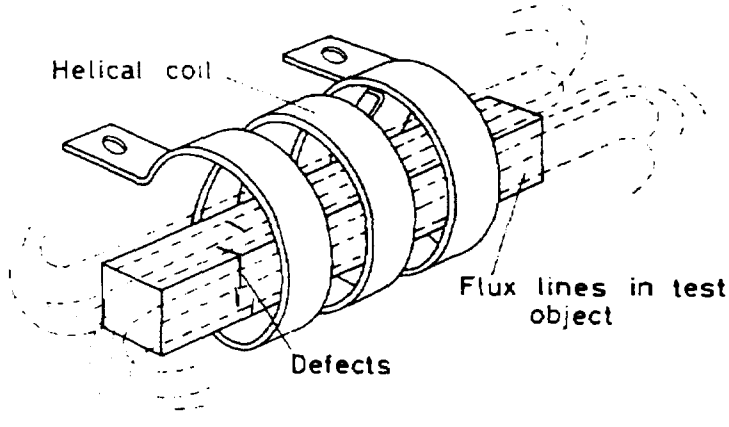


Figure 3.7 : Helical coil for magnetisation.

(c) Magnetization of irregular parts

Parts of irregular shape sometimes have to be tested. They can be tested using the magnetic particle inspection method. Local magnetization is created by applying prods to the area to be tested. The area is magnetized circularly and any defect in the path of the magnetic lines of force can be indicated as shown in Figure 3.8.

The inspection of irregular parts by this method is time consuming since a magnetizing current has to be applied many times to achieve thorough inspection of a component. However the testing time is not a large problem, due to the quick testing capability of the magnetic particle inspection method.

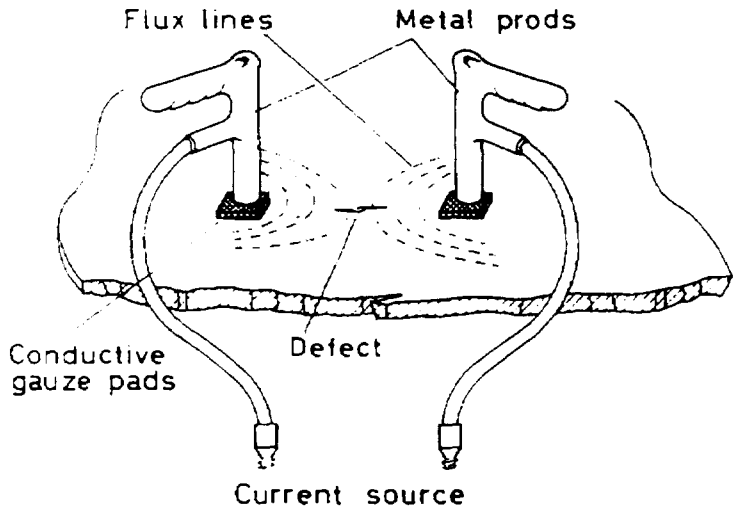


Figure 3.8 : Magnetization of irregular specimens.

3.3.2 General procedure for magnetic testing

The steps and sequence involved in the magnetic method are as follows:

(a) Preparation of the test specimen

Loose rust and scale should be removed from the component. Machined parts should be degreased using appropriate solvents. In painted parts the paint should be removed locally to provide adequate contact areas for the current flow tests. Parts with paint in the test area will only require degreasing unless the colour of the paint is the same as that of the particles in the ink to be used and is likely, therefore, to provide poor contrast. In the latter case a contrast aid may be applied. This is normally a thin white coating. The application of a white emulsion paint is an alternative procedure. Components which have been in a magnetic field may be carrying residual magnetism. It is advisable to remove this residual magnetism to avoid false indications.

b) Magnetization of the test specimen

The test specimen may be magnetized depending on its shape and configuration by using any of the methods outlined in Section 3.3.1. It is advisable to devise and write down the technique to be used listing the operations required with all details of directions of tests and jigs needed. Many components may not have simple geometric shapes but instead may have what can be considered to be combinations of simple shapes. In such cases more than one magnetizing technique may be necessary to be able to test the whole specimen. When multi-diameter or multi-thickness specimens are to be tested in the same direction, testing of the larger diameter/thickness portion will over-saturate the smaller diameter/thickness portion, therefore the lower value tests should be made first.

The sensitivity of defect detection improves with the level of magnetization. Theoretically a level just below saturation would give the most sensitive results but this is impractical owing to the variety of non-regular shapes encountered and therefore, in practice lower levels are quite adequate. For most critical work about 40% of saturation is sufficient. With this level of magnetization large defects of 2.5 mm depth below the surface can always be found and up to about 1.5 mm deep all defects of a serious nature can be detected.

Practically the saturation flux value for the test specimen may be found by increasing the flux level until background is formed. Variables affecting the flux for permanent magnets and electromagnets include the cross section and length of the test specimen and the total length of the flux path including the machine poles. For the current flow method a value of 9 A/mm of perimeter of the test specimen is the recommended level of magnetization for critical work. For basically round components this can be expressed as 28 A/mm of diameter. While testing using a coil, the factors that influence the magnetic flux are number of ampere turns of the coil, fill factor of the coil, length over diameter ratio of the test specimen and the coil shape. To obtain a suitable test value in this case, the current in the coil is increased with the component in position until saturation is obtained and the suggested standard would then be 40% of the saturation value. Alternatively for rigid coils and provided that the component is placed near the coil perimeter and has a cross-sectional area not more than 10% of the coil cross-sectional area, the test current may be calculated using the equation $A = 9000/CT$ where A is the current in amperes, C is the coil diameter in millimetres and T is the number of coil turns.

(c) Application of the magnetic powder

Magnetic particles are available in red or black colours. The red material improves visibility on dark surfaces. There are also fluorescent materials available. These magnetic particles may be applied to the test specimen either in dry or in wet form. If a dry powder is used it should be applied to the magnetized component such as to achieve an even distribution. Tapping the test specimen with a rubber hammer is often helpful. For the wet magnetic particles it is best that these are applied during magnetization. They should cease flowing just before excitation ceases. They can be applied to the test specimen by brush, ladle or hose. Whichever method is used, care should be taken to avoid violent flow over the test specimen, otherwise faint

indications from flaws are disturbed. Such faint indications will also be washed away if the magnetic particles are reapplied after the current has ceased to flow. The application of magnetic particles may also be made by immersing the test specimen in a suspension of particles. As the particles in the wet method are generally finer than those in the dry method the wet method is more sensitive for the detection of fine surface defects. On the other hand it is not as sensitive as the dry method for the detection of subsurface discontinuities. Greatest sensitivity is achieved through the use of fluorescent magnetic particles.

(d) Viewing and recording of indications

The whole of the surface under test should be viewed. Viewing of under surfaces may need a mirror. Bores may need special lighting and viewing of end faces may necessitate removing the test specimen from between the contacts. Doubtful indications are often more evident if the component is allowed to drain for a few minutes. Any indications found can be marked with a grease pencil after allowing the ink to drain. It is frequently desirable to record not only the appearance of indications on a part but also their locations. For a permanent record the indication can be lifted from the test specimen and transferred to white paper using adhesive tape.

(e) Demagnetization

For many industrial applications the tested specimens are required to be free from magnetism. Demagnetization may be achieved by inserting the part in the field of an alternating current solenoid and gradually withdrawing it from the field. Larger parts may be demagnetized by subjecting them to an alternating current field that is gradually reduced in intensity by means of a current controller.

When large masses of steel or iron are involved, alternating current has insufficient penetration to demagnetize such pieces thoroughly. In such cases direct current should be used. Hammering or rotating in the field will sometimes assist demagnetization. Heat treating or stress relief will demagnetize weldments and total demagnetization is always accomplished when the work piece is heated above the curie temperature of the metal. The efficiency of demagnetization should be checked by using a compass or a commercial magnetic field indicator.

3.3.3 Equipment for magnetic particle inspection

It is emphasized that magnetic particle testing is an important process in the production of steel components which are not checked at any subsequent manufacturing stage. The provision of adequate equipment for use by a reliable operator will more than justify the initial cost and will ensure that the tests are correctly carried out. Equipment is available in the range of from small hand tools to big universal type testing equipment. In both categories, i.e. portable and non-portable, more than hundred types are used in industry. Portable equipment can be taken to the site for the inspection of large castings, weldments, assembles or welded structures or parts of assemblies tested without disassembly. Small parts, on the other hand can be brought to a fixed inspection station. In industry, inspection is a part of the production line.

Therefore inspection of in-process parts can be done by sampling or on a 100% basis at one or more locations along the production line. Sometimes inspection is needed where mass production of a single piece is done. For this purpose specialized testing equipment may be best for minimum testing cost per piece. At other places inspection of various types of parts may be required in a very high volume. Here there is need for an equipment where eight, ten or twenty different parts can be inspected on a single piece of equipment in lots of several thousand per hour. In many industries various types of parts are produced on a low production basis. For this a single piece of test equipment can be used with greater efficiency. Other factors which need to be kept in view when selecting equipment are the types of defects of interest, the required sensitivity and whether the whole or a localized area of the test specimen is to be inspected.

Different types of equipment available in the market are briefly reviewed here. Hand operated small fixed or stationary units are widely used for small manufactured parts. These units normally contain a built-in tank with pump which agitates the wet particle bath and pumps inspection fluid through a hand held hose for application to test objects. A part is clamped within the magnetizing coil between the copper contact faces. At the operator's option, the parts can be magnetized circularly with current between the head, or longitudinally with current through the coil, or both if desired. while the part is magnetized, the operator applies the liquid inspection medium, and then views the surface for indications. Most units are provided with inspection hoods and black lights, so that fluorescent magnetic particles can be used. This increases the rate of inspection and reduces the possibility of missing an indication. This type probably accounts for about 75% of magnetic particle inspection.

For bulkier work upto say 1.5 m long and 0.3 m in diameter, more power is needed to maintain the desired flux level. Such units have a magnetizing current upto 5000 amp. a.c. and a magnetic field of about 1500 oersteds (120 K A/m). A demagnetizer which is built in can accommodate a part of 360 x 250 mm. Sensitivity may be controlled to reveal only surface cracks with a.c or surface and subsurface cracks with half wave current.

For site testing, equipment must be capable of being handled manually up ladders and to be located remote from mains supply. Many standard sizes of portable magnetic particle inspection equipment are in use. They vary from small hand held yokes made from permanent magnets to electromagnets.

Several types of completely automatic equipments are used for magnetic particle inspection in hundreds of plant locations. Inspection is carried out automatically on parts carried by a continuous conveyer. Loading and unloading may be manual or automatic. The inspector is required to view the parts as they pass on the conveyer and must only see and react to readily visible indications. Parts bearing indications are diverted for later evaluation and salvage or rejection. Accepted parts remain on the conveyer and pass through an automatic demagnetizer before being discharged from the unit. Such equipment permits a rapid and low-cost inspection where slower inspection may not be worth its cost. Special purpose equipment for checking automatically a large number of identical parts of simple form can be designed in such a way that a current flow test and a coil test are applied at the same time, thus enabling both longitudinal and transverse defects to be found.

3.3.4 Applications of the magnetic method of testing

In general engineering practice, a large proportion of components are made of steel or iron which are capable of being magnetized. This is fortunate because this testing method is not expensive and it can reveal all the surface faults in parts which are subjected to light stresses and fatigue and in those which have been cast, welded or heat treated during fabrication. Many inspection specifications for aerospace, atomic and other critical work specially call for this type of test.

When non metallic inclusions occur in areas of high stress or in certain special locations, they may be a cause for rejection. A subsurface condition which is much more likely to be dangerous is the presence of inclusions which were not plastic at the time of rolling or forging e.g. refractory materials. Usually the inclusions are very fine and are revealed with magnetic particle inspection only when they occur near the surface. They are most likely to be shown on highly finished surface by applyng the wet method with high magnetization levels. Inspection before machining is not helpful, and if inclusions are considered a cause for rejection, parts should be inspected after surface finishing.

Surface seams in rolled bars result from cracks or other defects (surface) in the billets from which they are rolled or from some defects introduced by the rolling operation itself. The great elongation of the metal draws out such surface defects, into long, straight seams, usually parallel to the direction of rolling. Cooling cracks which occur in rolled bars are similar to seams but usually differ in appearance in some respects. When magnetic particles are applied to such a surface for inspection, the indications are sharp and well defined, but deviate some what from the rolling direction.

Porosity in castings caused by gases trapped during the solidification of the molten metal can sometimes be located with magnetic particle inspection. Subsurface blow holes and thermal cracks in castings can also be revealed with magnetic particle inspection.

Magnetic particle inspection is used extensively on welds. It is possible to find porosity, slag inclusion shrink cracks, inadequate penetration and incomplete fusion. With d.c. magnetization a subsurface discontinuity like lack of penetration at a root can be revealed.

Cracks caused by faulty heat treatment processing are readily found with magnetic particle inspection. Such cracks may occur during either the heating or quenching cycle and may be enlargements of conditions existing in the part from some previous operation. Heat treatment cracks which are created by the quench cycle and which are also called quench cracks, are usually found at sharp changes of section, which cause unequal cooling rates, or at fillets or notches which act as stress concentration points.

Fatigue cracks are produced in service under repeated stress reversals or stress variation. A crack almost invariably starts at a highly stressed surface and propagates through the section until failure results. A fatigue crack will start more readily where design or surface condition provides a point of stress concentration. Sharp fillets, poor surface finish, seams, grinding cracks, and other such defects act as stress raisers and assist in the start of fatigue cracking.

All magnetic particle inspection to eliminate seams, inclusions, cooling cracks, laps, porosity, heat treatment cracks and grinding cracks is for the purpose of preventing fatigue or service failure after the part goes into service. Consistent use of magnetic particle inspection as well as other non-destructive tests in a well planned preventive maintenance programme can in many cases reduce service failure from fatigue to practically zero.

3.3.5 Range and limitations of magnetic particle inspection

Magnetic particle testing is a method of finding surface and near surface defects in any steel or iron sample capable of being magnetized. It is essential that the flux path crosses the flaw and ideally should be at right angles to it. Fortunately, with an adequate level of magnetization, defects oriented by as much as 50 degrees with respect to the direction of the flux will show up and any object can be tested completely provided at least two tests are made. The flux direction in the object for the second test should be at right angles to the flux direction for the first.

To ensure an adequate test, the factors that need to be considered include the shape of the component, the dimensions of the component, the magnetic permeability, surface finish, possible defects and their orientation, suitable flux direction and strength and a suitable testing stage during manufacturing. Unless due consideration is given to all these factors, the test is unreliable, although it may reveal some defects, but it is quite possible that serious defects may not be revealed.

Because every component differs and at least two tests are required to find all defects it is good to establish a proper technique for each. For components having complex shapes, this technique may consist of as many as a dozen tests at varying field strengths and using different methods to ensure 100 percent coverage.

Provided that adequate equipment is available, it is feasible to test any type and size of magnetic object. The size of defects which can be detected will depend upon surface finish and other factors.

Magnetic particle inspection is not expensive. The test can be performed in the presence of an overlay of paint or non-magnetic plating. The inspection can be undertaken by semi-skilled labour without requiring elaborate protection such as that needed for radiography.

The presence of non-conducting surface coatings, such as paint, may preclude the use of contact current flow tests. The material must be capable of being magnetized which precludes the testing of austenitic steels and other non-magnetic materials. Since every test requires at least two directions of flux, components of complex shapes may need numerous tests which becomes cumbersome and time-consuming. Demagnetization is another of the shortcomings. The ink particles can clog fine passages and their removal is sometimes laborious.

3.4 EDDY CURRENT TESTING

An alternating current of known frequency is applied to an electric coil placed adjacent to the material to be inspected. This current will produce its own magnetic field known as the excitation field and will also induce currents in the metal part

known as eddy currents according to Faraday's law of electromagnetic induction. These eddy currents will produce their own magnetic field which will oppose the excitation field. The resultant field is thus reduced which will change the coil impedance.

In Figure 3.9 an alternating current of a given frequency is generated in the primary or exciting coil. An alternating magnetic flux is consequently produced. This induces an alternating current of the same frequency in the secondary coil. With the introduction of the specimen, the alternating flux of the primary induces in it (the specimen) an eddy current flow which gives rise to an alternating magnetic flux in the opposite direction. The current in the secondary coil is consequently reduced. For given conditions the reduction in current should be equal for all identical specimens placed in the same position relative to the coils. Any observed inequality in the value of the reduced current could indicate the presence of a defect, a change in dimensions, or a variation in the electrical conductivity or in the magnetic permeability of the test specimen due perhaps, to a change in its physical or chemical structure.

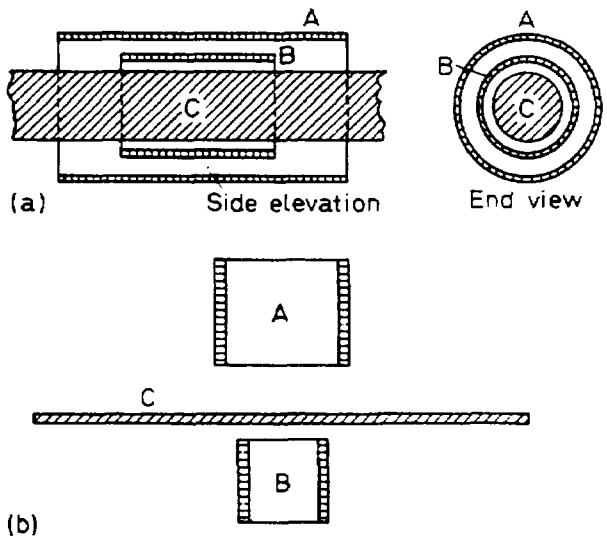


Figure 3.9 : Arrangement of test coils and the test specimen in eddy current testing.

The coil impedance, which is usually measured in practice instead of the current or flux, is a vector quantity having resistive and inductive components. These are 90° out of phase with each other. The other quantity that may be measured in practice is the voltage across the coil. The coil impedance as well as voltage is related to the effective permeability of the test specimen, the test frequency of the coil, the limiting or boundary frequency of the test specimen and the fill factor of the coil. This relationship is shown in Figure 3.10. The boundary frequency for non-ferromagnetic materials is defined as

$$f_g = 2/(\pi \mu_0 \sigma . D^2)$$

where μ_0 is the permeability for air and almost all other non-ferromagnetic materials, σ is the electrical conductivity and D the diameter of the specimen. The fill factor is defined as $\eta = (D/D')^2$ where D' is the inside diameter of the coil.

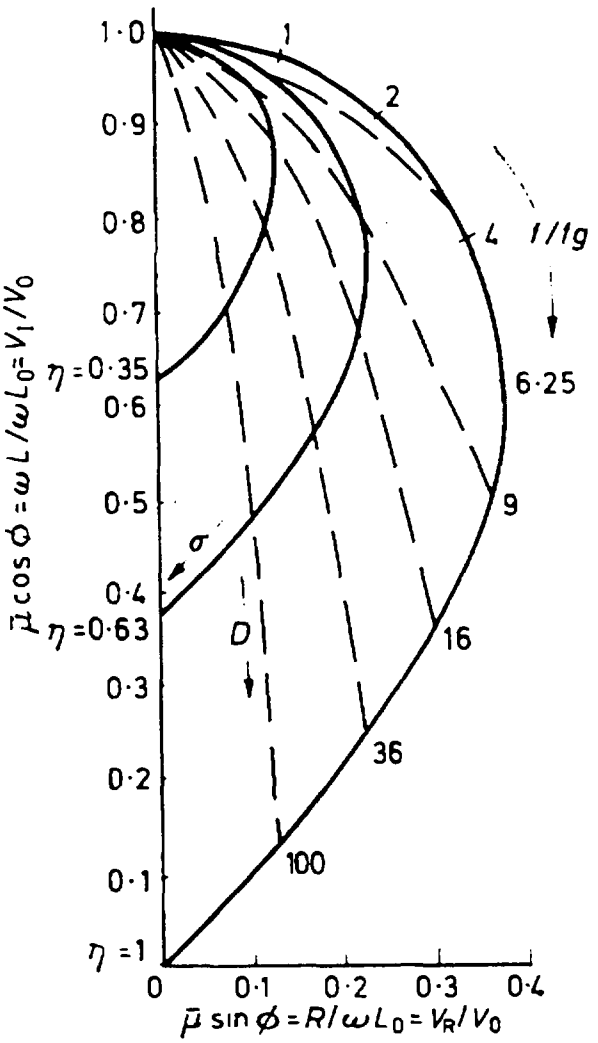


Figure 3.10 : Typical impedance plane diagram showing relationships between f/fg, η, D and σ.

Figure 3.10 shows variations of impedance with frequency for different values of η. The dashed lines join all points on the curves corresponding to similar values of f/f_g. Continuous lines represent variations of conductivity for constant diameter D and the dashed lines represent changes in D for constant values of σ.

For ferromagnetic materials the relative permeability is greater than unity and therefore f_g must be defined as $2/(\pi\ \mu_r\ \mu_0\ \sigma.\ D^2)$. If the specimen is kept magnetized to well above saturation level then the value of μ_r can be taken as unity and curves such as in Figure 3.10 remain valid. But if the specimen is not saturated magnetically then fresh curves have to be drawn.

The inspection frequencies used in eddy current inspection range from 200 Hz to 6 MHz. The choice of the frequency depends on the thickness of material, the desired depth of penetration, the degree of sensitivity or resolution and the purpose of inspection. Selection of inspection frequency is normally based on a compromise between the depth of interest and sensitivity to flaws. Increasing the frequency lowers the depth of penetration but increases the resolution and vice versa. Normally the highest inspection frequency compatible with the penetration depth required is selected. For surface flaws frequencies upto several mega hertz may be used. For the inspection of ferromagnetic materials, relatively low frequencies are normally used.

The inspection probe will give a certain indication on the instrument when placed in air. This indication will begin to change as the probe is brought close to the test piece and will continue to change until the probe is directly on the piece. This change in indication with change in spacing between the probe and the material to be tested is termed lift-off. Lift off has a drawback as well as an advantage. The drawback is that many indications resulting from conditions of primary interest are masked by small changes in spacing. The advantage is that by utilizing the lift-off effect, the eddy current testing instrument can be employed excellently for measuring non-conductive coating such as paint and anodized coating in metals.

When an eddy current inspection probe approaches the edge of a part, the eddy currents are distorted because they are unable to flow beyond it. The indication obtained from it is called "edge-effect" and is very dominant, thereby, limiting inspection near edges. It is not advisable to inspect any closer than about 6 mm from the edge of a part.

The distribution of eddy currents in the part being inspected is such that these are densest at the surface closest to the probe and progressively become less dense with increasing distance from the surface. This phenomenon is known as skin-effect. The depth at which the density is reduced to about 37% of the density at the surface is defined as standard depth of penetration. It depends on the electrical conductivity, magnetic permeability of the material being inspected and the frequency of exciting signal.

3.4.1 Equipment and procedure for eddy current testing

The main component of eddy current equipment is the probe of which there are several different types. The probe could be the encircling type, the internal type or the external type. The main coil arrangements which may be present in these probes can be divided mainly into three categories depending upon the methods of measurement. In the absolute method the primary and secondary coil are matched so that in the absence of any test specimen the voltages across them are equal and opposite. Introduction of the test piece results in a change in impedance and a voltage change appears which is measured.

The comparison method consists of the use of two identical coil assemblies. A standard defect free specimen is placed in one coil and the test specimen in the other. Changes arising from the differences in the two samples are measured. In the auto-comparison method two different parts of the same sample are compared with each other.

A wide variety of eddy current testing equipment exists, but only some of its typical types are mentioned here. The simplest is the AC bridge. The bridge is unbalanced when a probe passes over the defect because its impedance is changed. Forster's analysis has been applied in the design of some versatile instruments which can be used for conductivity testing, investigation of dimensional variations and flaw detection. The two components of the voltage across the secondary coil are separated in phase and fed to the X and Y plates of an oscilloscope. On the screen appears a bright spot representing a point on the Forster's impedance analysis graph. The movement of this spot is then related to different measurements such as crack detection, conductivity measurements and determination of dimensional variations. Such instruments can be applied to automatic testing for example, sorting of materials.

Another type of Forster's equipment uses the ellipse method. A reference voltage in phase with the signal applied to the primary coil is fed to the X-plates of a cathode ray oscilloscope. The output voltage from the secondary coil is fed to the Y-plates. Now two vibrations at right angles to one another produce a Lissajous figure, which in this case is an ellipse. The shape of this ellipse depends on the phase difference between the two voltages and hence the phase angle of the impedance. Different types of defects in the specimen, say cracks, correspondingly produce different shapes of the ellipse. The ellipse degenerates into a straight line for a crack-free specimen. Such equipment can be used for testing ferromagnetic as well as non-ferromagnetic materials provided that a DC magnetic saturation unit is used. There is equipment available which is used for testing tubes, rods and bars which are passed through an encircling coil assembly at a steady speed of up to 100 m/s. The test coil assembly consists of two single coils of slightly different impedances placed next to one another and wound in opposite directions. They are excited by an oscillator. The impedances of these coils are balanced by two comparison coils and a potentiometer device. The effect of eddy currents on the test coils is to produce two opposing out-of-balance signals the resultant of which passes through an amplifier, a phase sensitive detector and a filter to an output stage. A reference voltage supplied by the oscillator to the phase sensitive detector enables one to phase-out unwanted components. This equipment is available for use at different frequencies. The output of such instruments can be connected with a high speed pen recorder to mark the position of defects on the test specimen.

Some equipment employs the principle of frequency modulation and is used for testing rods and tubes in continuous motion. The velocity of the component relative to the coil and the changes in the impedance of the coil combine to give rise to modulation of the operating frequency while dimensional changes cause a somewhat higher frequency modulation. The sharp discontinuities produced by defects such as cracks and blow-holes give rise to modulations at very much higher frequencies. The equipment can be operated at different frequencies. The signals are detected with an oscilloscope and a pen recorder.

The eddy current equipment for measuring conductivity of materials employs a single probe coil acting simultaneously as an exciter and pick-up. The probe is moved by hand over the surface of the test material. The impedance of the coil is initially balanced with that of a similar coil inside the main body of the apparatus. Changes in the impedances of the probe coil due to eddy currents in the material under test give rise to an out-of-balance voltage which is indicated by a meter directly in units of conductivity. The frequency chosen for operation depends on the range of values of conductivity to be measured and the thickness of the material. Applications of this type of equipment include sorting of mixed materials, hardness testing, control of homogeneity, measurement of porosity and investigating degrees of heat treatment for non-ferromagnetic materials.

The determination of the thickness of non-conducting coatings on non-ferromagnetic metal surfaces is done with the help of eddy current equipment by measuring the lift-off effect for a probe coil. The probe coil is coupled by a transformer to a tuned circuit which is connected to a highly sensitive and stable frequency oscillator. When the probe is placed in contact with the surface of the coating, the oscillations decrease in amplitude by an amount depending on the coating thickness. The amplitude is then restored to a fixed level indicated on a meter by manipulating a potentiometer calibrated in the appropriate units of thickness. The potentiometer readings are zeroed by locating the probe on an uncoated metal surface.

Ferromagnetic materials can be tested by subjecting them to magnetic hysteresis. The equipment for this includes two identical coil assemblies of either the encircling or probe type which are located at right angles to one another in order that the flux passing through one set of coils does not pass through the other. The secondary coils are both connected through an amplifier to the Y-plates of an oscilloscope, the X-plates of which are controlled by a time base. An alternating current is fed through each primary coil in such a way that the two currents are 180 degree out of phase with one another. The time base can be adjusted so that a single cycle, or part of a cycle of the output from each secondary coil is displayed on the screen. The two signals are superimposed on one another and in the absence of a test sample the phases cancel out and a horizontal straight line is observed. When a test specimen is introduced in one of the coils, the material undergoes magnetic hysteresis the loop of which is modified by the action of induced eddy currents. The straight line becomes disturbed and the trace assumes a shape that is characteristic of the electrical conductivity, the magnetic permeability and the dimensions of the material. On applying an identical specimen to the second coil in exactly the same relative position, the trace again becomes a straight line. If, however the permeability, conductivity or dimensions of two specimens differ in any way the trace assumes a shape which is characteristic of this difference. The equipment can be used to test ferromagnetic components of various shapes and sizes for such properties as hardening, the existence of internal stresses, machinability, etc. Manufacturers usually supply along with the equipment standard shapes of traces characteristic of some of these properties.

3.4.2 Applications of eddy current testing

Most of the applications of eddy current testing have already been mentioned while describing the basic principles, equipment and procedures in the previous sections. In the following, a summary of these applications is being given.

Eddy current testing is employed for the detection and measurement of defects such as cracks, porosity, blowholes, inclusions, overlaps, shrinkages and soft spots in a wide variety of test specimens in solid cylindrical, hollow cylindrical or other complex shapes. Corrosion and cracking due to stress corrosion can also be detected. Changes in electrical conductivity and permeability can be measured which in turn have a bearing upon the material properties such as hardness, homogeneity, degree of heat treatment, existence of internal stresses, decarburization, diffusion, alloy composition, presence of impurities, etc. Thickness measurements can be made on metallic plates, foils, sheets, strips, tubes and cylinders. Typically it is possible to determine the thickness of non-metallic coatings on metals such as for example the insulating layers on cables, non-conducting paints on some aircraft castings and anodic coating on aluminium alloy surfaces. Dimensions such as diameters of cylindrical specimens can also be determined. The materials can be automatically sorted in a production process. Since the method is adaptable to automation high speed inspection of small diameter tubings such as those used in steam generators, heat exchangers and as cladding for nuclear reactor fuel elements is possible. Here the characteristics of fuel tubing such as inner and outer diameters, eccentricity, wall thickness and the presence of defects are determined. It is also possible to inspect welded small bore piping. By using encircling type probes large diameter pipes can be inspected. Similarly long bars and wires can be speedily inspected. In tube testing the eddy current method also allows high speed detection of intergranular corrosion on the inside surface. In some applications round metallic spheres and balls are inspected by eddy currents.

3.4.3 Range and limitations of eddy current testing

Eddy current testing can be carried out on all materials which conduct electricity. Both ferromagnetic and non-ferromagnetic materials can be tested. The method has the advantage that contact with the test specimen is not necessary. No couplant is therefore needed. The probe coils can be made with very small diameters and thus can detect the presence of very small flaws.

The sensitivity of the coils can be increased by the insertion of high permeability cores such as ferrite rods which produce very sensitive focused coils. Long wire, tubes, rods, etc. can be tested by feeding them through the coils at a constant speed. Since the technique is susceptible to automation, fast scanning up to say 100 m/s is possible and it allows rapid 100% inspection of production items. The relative cost of inspection is therefore low. Under certain circumstances the indications produced are proportional to the actual size of the defect. Thus the tests can be useful for grading and classifying.

Due to the skin effect the depth of penetration into the test specimen is limited and therefore the application of the technique is limited to detection of surface and close-to-surface defects. Also because of this phenomenon the measurement of wall thicknesses is limited to thin wall tubing and to smaller thicknesses of materials. The lift-off effect is undesirable in most testing cases. The technique is limited to inspecting materials that are good conductors of electricity. It presents some difficulties when attempts to make absolute measurements are made. For manual testing there is a need to have properly trained, qualified and experienced operators.

3.5 RADIOGRAPHIC TESTING

3.5.1 Fundamental principles

3.5.1.1 The method of radiographic testing

The method of radiographic testing involves the use of a source of radiation from which the radiations hit the test specimen, pass through it and are detected by a suitable radiation detector placed on the side opposite to that of the source. This is schematically shown in the Figure 3.11. While passing through the test specimen the radiations are absorbed in accordance with the thickness, physical density and the internal defects of the specimen and the detector system therefore receives the differential radiations from different parts of a defective specimen which are recorded onto the detector.

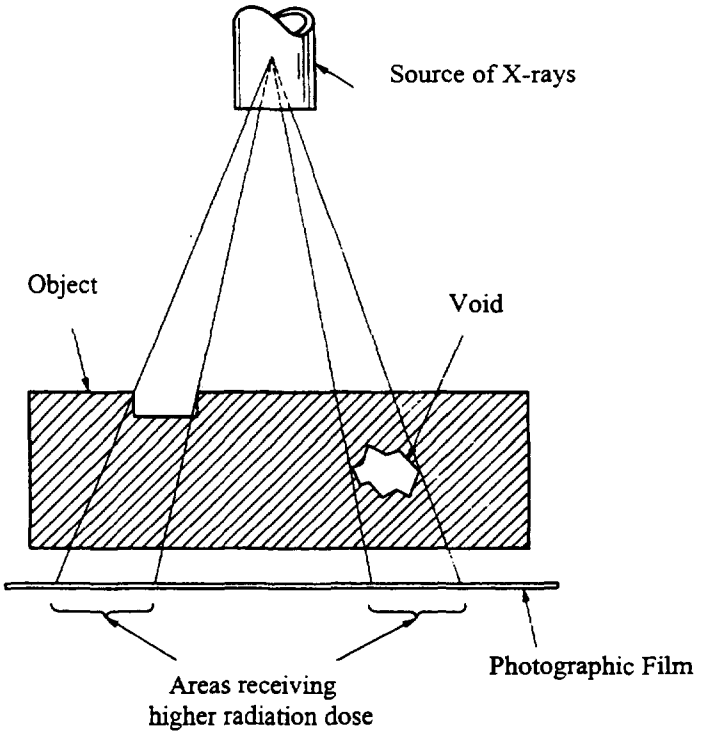


Figure. 3.11 : Arrangement of source, specimen and film in a typical radiographic set up.

3.5.1.2 Properties of radiations

X-rays and gamma rays are electromagnetic radiations which have the following common properties.

(i) They are invisible.
(ii) They cannot be felt by human senses.
(iii) They cause materials to fluoresce. Fluorescent materials are zinc sulfide, calcium tungstate, diamond, barium platinocyanide, napthalene, anthracene, stilbene, thalium activated sodium iodide etc.
(iv) They travel at the speed of light i.e. 3×10^{10} cm/sec.
(v) They are harmful to living cells.
(vi) They can cause ionization. They can detach electrons from the atoms of a gas, producing positive and negative ions.
(vii) They travel in a straight line. Being electromagnetic waves, X-rays can also be reflected, refracted and diffracted.
(viii) They obey the inverse square law according to which intensity of X-rays at a point is inversely proportional to the square of the distance between the source and the point. Mathematically $I \alpha 1/r^2$ where I is the intensity at a point distant r from the source of radiation.
(ix) They can penetrate even the materials through which light cannot. Penetration depends upon the energy of the rays, the density and thickness of the material. A monoenergetic beam of X-rays obeys the well known absorption law, $I = Io \exp(-\mu x)$ where Io = the incident intensity of X-rays and I= the intensity of X-rays transmitted through a thickness x of material having attenuation coefficient μ .

(x) They affect photographic emulsions.
(xi) While passing through a material they are either absorbed or scattered.

Properties (vii), (viii), (ix), (x), (xi) are mostly used in industrial radiography.

3.5.1.3 Sources for radiographic testing

(i) X ray machines

X rays are generated whenever high energy electrons hit high atomic number materials. Such a phenomenon occurs in the case of X ray tubes, one of which is shown in Figure 3.12. The X ray tube consists of a glass envelope in which two electrodes called cathode and anode are fitted. The cathode serves as a source of electrons. The electrons are first accelerated by applying a high voltage across the cathode and the anode and then stopped suddenly by a solid target fitted in the anode. The sudden stoppage of the fast moving electrons results in the generation of X rays. These X rays are either emitted in the form of a cone or as a 360 degree beam depending upon the shape and design of the target. The output or intensity of X rays depend upon the kV and the tube current which control the number of electrons emitted and striking the target. The energy of X rays is mainly controlled by the voltage applied across the cathode and the anode which is of the order of kilovolts. The effect of a change in the tube current or the applied voltage on the production of X rays is shown in Figure 3.13.

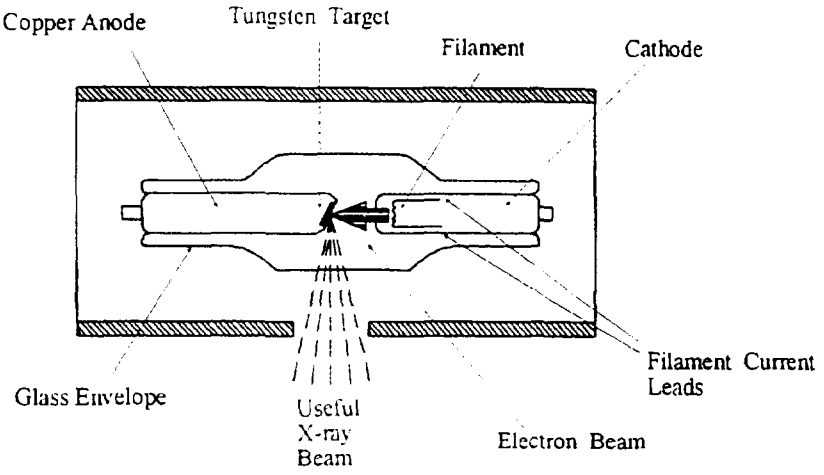


Figure 3.12 : Sketch of an X ray tube.

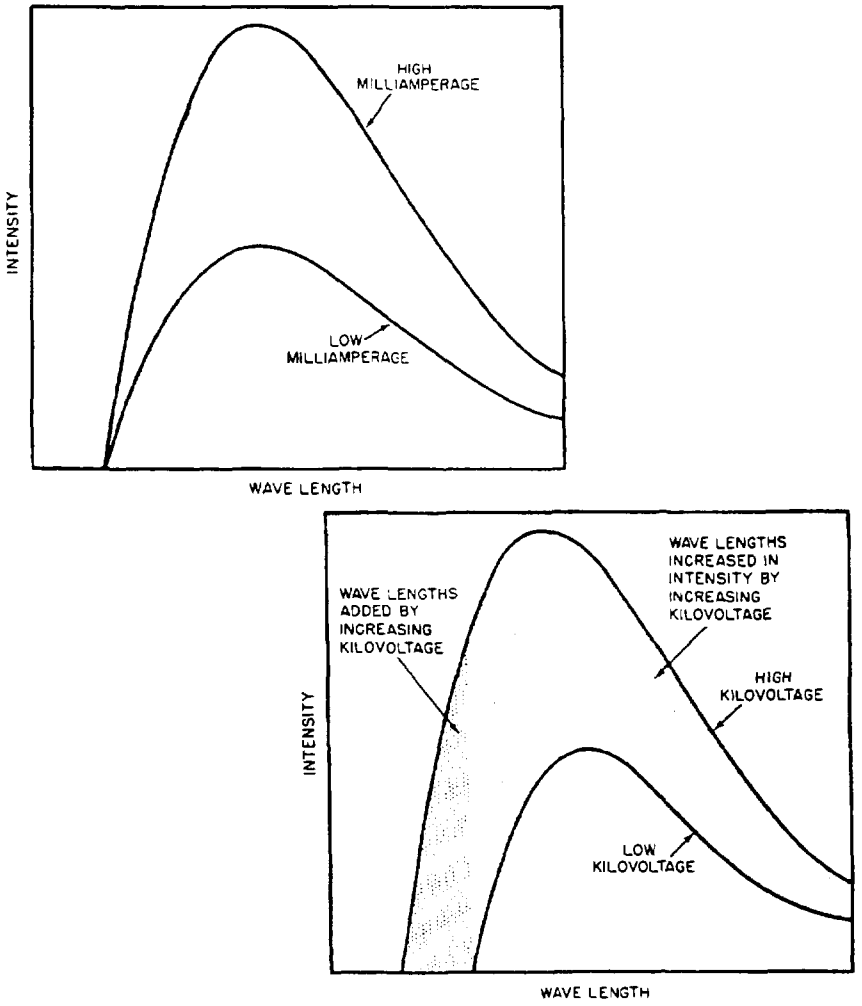


Figure 3.13 : Effect of tube current (mA) and voltage (kV) on the intensity of X rays.

There is a variety of X ray machines available for commercial radiographic testing. Some of these emit X rays in a specified direction while others can give a panoramic beam. There are machines which have a very small focal spot size for high definition radiography. These are called micro focus machines. Some machines are specially designed to give very short but intense pulses of X rays. These are called flash X ray tubes and are usually used for radiography of objects at high velocity. Typically X ray machines of up to a maximum of about 450 kV are commercially available for radiographic testing.

(ii) Gamma ray sources

These are some elements which are radioactive and emit gamma radiations. There are a number of radioisotopes which in principle can be used for radiographic testing. But of these only a few have been considered to be of practical value. The characteristics which make a particular radioisotope suitable for radiography include the energy of gamma rays, the half life, source size, specific activity and the availability of the source. In view of all these considerations the radioisotopes that are commonly used in radiography along with some of their characteristics are given in Table 3.1.

(iii) Radiographic linear accelerators

For the radiography of thick samples, X ray energy in the MeV range is required. This has now become possible with the availability of radiographic linear accelerators. In a linear accelerator the electrons from an electron gun are injected into a series of interconnected cavities which are energized at radio frequency (RF) by a klystron or magnetron. Each cavity is cylindrical and separated from the next by a diaphragm with a central hole through which the electrons can pass. Due to the imposed RF, alternate diaphragm hole edges will be at opposite potentials at all times and the field in each cavity will accelerate or decelerate the electrons at each half cycle. This will tend to bunch the electrons and those entering every cavity when the field is accelerating them will acquire an increasing energy at each pass. The diaphragm spacing is made such as to take into account the increasing mass of electrons as their velocity increases. They impinge on a target in the usual way to produce X rays. Linear accelerators are available to cover a range of energies from about 1 MeV to about 30 MeV covering a range of steel thicknesses of up to 300 mm. The radiations output is high (of the order of 5000 Rad per minute) and the focal spot sizes usually quite reasonable to yield good quality radiographs at relatively low exposure times.

(iv) Betatron

The principle of this machine is to accelerate the electrons in a circular path by using an alternating magnetic field. The electrons are accelerated in a toroidal vacuum chamber or doughnut which is placed between the poles of a powerful electromagnet. An alternating current is fed into the energising coils of the magnet and as the resultant magnetic flux passes through its zero value, a short burst of electrons is injected into the tube. As the flux grows the electrons are accelerated and bent into a circular path. The magnetic field both accelerates the electrons and guides them into a suitable orbit and hence, in order to maintain a constant orbit,

TABLE 3.1 : TYPICAL RADIOACTIVE SOURCES FOR INDUSTRIAL RADIOGRAPHY.

Characteristics / Source	Half life	Gamma ray energies (MeV)	RHM value per curie	Optimum thickness range (mm of steel)	Half value layer (mm of lead)
Thulium-170	128 Days	0.87, 0.52	0.0025	2.5 to 12	-
Cobalt-60	5.3 Years	1.17, 1.33	1.33	50 to 150	13
Iridium-192	74.4 Days	0.31, 0.47, 0.64	0.5	10 to 70	2.8
Caesium-137	30 Years	0.66	0.37	20 to 100	8.4

these two factors must be balanced so that the guiding field at the orbit grows at an appropriate rate. The acceleration continues as long as the magnetic flux is increasing, that is, until the peak of the wave is reached; at this point the electrons are moved out of orbit, either to the inner or outer circumference of the doughnut, by means of a DC pulse through a set of deflecting coils. The electrons then strike a suitable target. The electrons may make many thousands of orbits in the doughnut before striking the target, so that the path lengths are very great and the vacuum conditions required are in consequence very stringent. The radiation from betatrons is emitted in a series of short pulses. In order to increase the mean intensity some machines operate at higher than mains frequency. Most betatrons designed for industrial use are in the energy range of 6–30 MeV. Betatrons in general have a very small focal spot size typically about 0.2 mm, but the X ray output is low. Machines are built in the higher energy range in order to obtain a higher output, but this brings the disadvantages of a restricted X ray field size.

3.5.1.4 Films for radiographic testing

The detection system usually employed in radiographic testing is the photographic film usually called an X ray film. The film consists of a transparent, flexible base of clear cellulose derivative or like material. One or both sides of this base are coated with a light sensitive emulsion of silver bromide suspended in gelatin. The silver bromide is distributed throughout the emulsion as minute crystals and exposure to radiation such as X rays, gamma rays or visible light, changes its physical structure. This change is of such a nature that it cannot be detected by ordinary physical methods, and is called the latent image.

However, when the exposed film is treated with a chemical solution (called a developer) a reaction takes place causing the formation of tiny granules of black metallic silver. It is this base, that constitutes the image. Figure 3.14 is an expanded pictorial view of the general make up of a film.

Radiographic film is manufactured by various film companies to meet a very wide diversified demand. Each type of film is designed to meet certain requirements and these are dictated by the circumstances of inspection such as (a) the part (b) the type of radiation used (c) energy of radiation (d) intensity of the radiation and (e) the level of inspection required. No single film is capable of meeting all the demands. Therefore a number of different types of films are manufactured, all with different characteristics, the choice of which is dictated by what would be the most effective combination of radiographic technique and film to obtain the desired result.

The film factors that must be considered in choosing a film are : speed, contrast, latitude and graininess. These four are closely related; that is, any one of them is roughly a function of the other three. Thus films with large grain size have higher speed than those with a relatively small grain size. Likewise, high contrast films are usually finer grained and slower than low contrast films. Graininess, it should be noted, influences definition or image detail. For the same contrast, a small grained film will be capable of resolving more detail than one having relatively large grains. The films are generally used sandwiched between metallic screens, usually of lead. These screens give an intensification of the image and thus help to reduce the exposure times besides cutting down the scattered radiation.

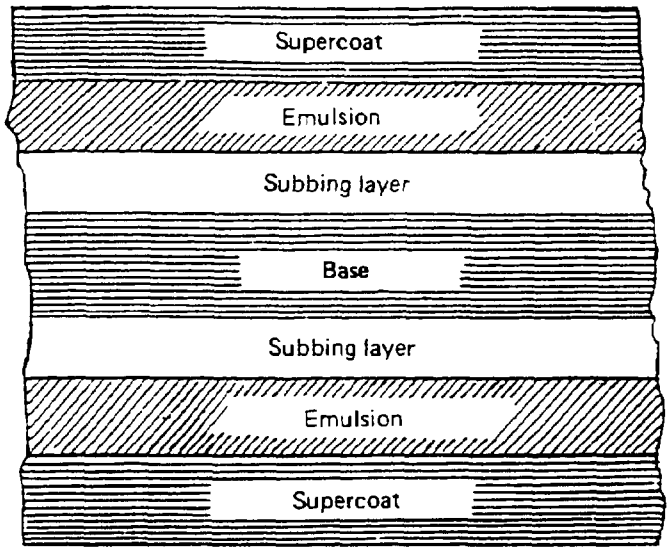


Figure 3.14 : Construction of radiographic films.

3.5.2 General procedure for radiographic testing

The test specimen is first of all properly cleaned and visually inspected and all the surface imperfections are noted. A properly selected film, usually sandwiched between intensifying screens and enclosed in a light proof cassette is prepared. The

source of radiation, the test specimen and the film are arranged as shown in Figure 3.11. Image quality indicators and lead identification letters are also placed on the source side of the test specimen. From a previously prepared exposure chart for the material of the test specimen, the energy of radiations to be used and the exposure (intensity of radiations × time) to be given are determined. Then the exposure is made. After the source of radiation has been switched off or retrieved back into the shielding (in case of gamma ray source), the film cassette is removed and taken to the dark room. In the dark room, under safe light conditions, the film is removed from the cassette and the screens and processed. The processing of the film involves mainly four steps. Development reduces the exposed silver bromide crystals to black metallic silver thus making the latent image visible. Development is usually done for 5 minutes at 20°C. After development the film is fixed whereby all the unexposed and undeveloped crystals of film emulsion are removed and the exposed and image-forming emulsion is retained on the film. The fixing is done for approximately 2–6 minutes. The film is then washed preferably in running water for about 20–30 minutes and dried. Finally the film is interpreted for defects and a report compiled. The report includes information about the test specimen, the technique used and the defects. It also sometime says something about acceptance or rejection of the reported defects. The report is properly signed by responsible persons.

3.5.3 Different forms of radiographic testing

(i) Fluoroscopy

In the general radiographic process, if the film is replaced by a fluorescent salt screen then the image of the test specimen can be visually seen. The X rays passing through the object excite the fluorescent material producing bright spots in the more heavily irradiated areas. The fluorescent screen may be viewed directly or by means of a mirror or by using a camera and a closed circuit television. The whole set-up of X ray tube, the test specimen and the fluorescent screen are encased in a protective shielding.

In many cases castings of up to about 10 mm thickness, thin metal parts, welded assemblies and coarse sandwich constructions are screened by this method and castings with obvious large defects are rejected before usual inspection using film radiography.

Plastic parts may be checked for the presence of metal particles or cavities. Other applications include inspection of electrical equipment such as switches, fuses, resistors, capacitors, radio tubes, cables and cable splices in which breaks of metal conductors, short circuiting or wrong assembly may cause troublesome electrical testing. Ceramics, fire bricks and asbestos products lend themselves perfectly to fluoroscopy. Packaged and canned foods are examined for the amount of filling and for the presence of foreign objects.

(ii) Micro radiography

Specially prepared thin samples are radiographed at extremely low energies (e.g. 5 KV) on an ultrafine grain film. The radiograph when enlarged gives the structural

details of the specimen. Micro-radiography is mainly applied in metallurgical studies.

(iii) Enlargement radiography

In some situations an enlarged image of an object is desired. To get the enlargement of the image the object to film distance is increased. To overcome the penumbral effects a source of an extremely small size is used.

(iv) High speed or flash radiography

For the radiography of moving objects, the exposure time should be very small and, at the same time, the intensity of the X rays should be extremely high. This is achieved by discharging huge condensers through special X ray tubes which give current of the order of thousands of amperes for a short time (of the order of a millionth of a second). This technique is normally applied in ballistics.

(v) Auto radiography

In this case the specimen itself contains the material in radioactive form. When a film is placed in contact with the specimen, an autoradiograph is obtained showing the distribution of the radioactive material within the specimen. The technique is mainly used in the field of botany and metallurgy.

(vi) Electron transmission radiography

A beam of high energy X rays is used to produce photo-electrons from a lead screen. These electrons after passing through the specimen (of very low absorption like paper, etc.) expose the film and an electron radiograph is obtained.

(vii) Electron emission radiography

In this case a beam of X rays is used to produce photoelectrons from the specimen itself. These electrons expose the film which is placed in contact with the specimen. Since emission of electrons depends upon atomic number of an element, the electron emission will give the distribution of elements of different atomic numbers.

(viii) Neutron radiography

In this case a neutron beam is used to radiograph the specimen. The recording system will, therefore, not be a photosensitive film since it is insensitive to neutrons. The following methods are used to record the image:

(1) A gold foil is used which records the image, in terms of the activity produced. This image can be transferred onto a film by taking an autoradiograph of the foil. Some other suitable materials such as indium and dysprosium can replace gold.

(2) The metallic foil upon neutron bombardment does not become radioactive but instead emits spontaneous gamma rays which expose the film placed in contact with it. Examples of metals suitable for this are lithium and gadolinium.

(3) Neutrons transmitted through the specimen are made to strike a thin neutron scintillator plate. The scintillations thus produced expose the film which is in contact with the scintillator.

In certain cases neutron radiography is advantageous as compared to X or gamma radiography, for example:

(a) If the specimen is radioactive.

(b) If the specimen contains thermal neutron absorbers or light elements.

(c) Two elements whose atomic number is not very different may be easily distinguished.

(ix) Proton radiography

For special type of studies a proton beam can also be used. The number of protons transmitted through a specimen whose thickness is close to the proton range is very sensitive to exact thickness. This helps in detecting very small local variations in density and thickness.

(x) Stereo radiography

Two radiographs of the specimen are taken from two slightly different directions. The angle between these directions is the same as the angle subtended by the human eyes while viewing these radiographs. In the stereo viewer the left eye sees one radiograph and the right eye the other. In this way a realistic three dimensional effect is obtained giving the visual assessment of the position of the defect.

(xi) Xeroradiography

This is considered as a "dry" method of radiography in which a xerographic plate takes the place of X ray film. The plate is covered with a selenium powder and charged electrostatically in the dark room. Exposure to light or radiation causes the charge to decay in proportion to the amount of radiation received and a latent image is formed.

The developing powder is sprayed on the plate in a light-tight box. The particles are charged by friction while passing through the spray nozzle. White powders have best contrast with the black selenium surface but present problems in transferring the picture to paper. Coloured powders on transfer produce negative images while fluorescent powder gives the same picture as white powder and can be viewed under black light both before and after transfer.

3.5.4 Personal safety and radiation protection

Nuclear radiations are harmful to living tissues. The damage done by radiations is sinister as human senses are not capable of detecting even lethal doses of radiation. The dose of radiations absorbed by human body is expressed in mSv (1 mSv = 100 rem = 1J/kg) which takes into account the biological effectiveness of different types of radiations such as alpha particles, gamma rays, X rays and neutrons, etc. The overall outcome of exposure to radiation is initiated by damage to the cell which is the basic unit of the organism. The effects of radiation may be deterministic or stochastic, early or late, of somatic or genetic type.

Somatic effects depend upon three main factors.

(a) First of these factors is the rate at which the dose is administered. Cells begin the repair processes as soon as some degree of damage has been received. When the body is able to keep up with the damage, no injury or pathological change will be seen in the irradiated individuals. However, the same amount of radiation given all at once would produce a more severe reaction.

(b) The second is the extent and part of the body irradiated. It is known that certain cells are more sensitive to radiation than others. Hence the overall effect of radiation depends on the extent and part of the body irradiated.

(c) The third important factor is the age of the affected individual, persons growing physically are in an accelerated stage of cells reproduction and most of the cells in the body are dividing and hence sensitive to radiation. For this reason an exposure of a given amount should be considered more serious for a young person than for an adult.

The somatic effects can either be immediate or delayed. Given below is a summary of immediate effects when the whole body is acutely irradiated with a range of radiation doses:

0–0.25 Sv: No manifested injuries and no clinical effects. Increase of frequency of chromosomal observations in peripheral lymphocytes above 0.15 Sv whole body dose.

0.5–1 Sv: Some changes in blood count picture i.e. reduction in lymphocytes and neutrophils with delayed recovery. Delayed effects may shorten life expectancy. No clinical symptoms .

1–2 Sv: Mild degree of ARS (acute radiation syndrome). Nausea, fatigue, dizziness. Vomiting in 10–50% cases within 24 hours starting 2 hours after exposure or later. Latent period about 3 to 4 weeks. Following the latent period, clinical symptoms appear in a more severe manifestation. No disability.

2–4 Sv: Moderate ARS: nausea, fatigue, dizziness, loss of appetite. Vomiting within 2 hours in 70–90% of exposed persons. Latent period of 2 to 3 weeks where the victim seems relaxed and recovering. The critical period follows with epilation, loss of appetite and general weakness accompanied by fever, inflammation of the mouth and throat, diarrhoea, nose bleeding. Death due to infections could occur in 0–50% of the exposed individuals within 2 months without proper treatment with antibiotics and fluid replacement .

4–6 Sv: Severe ARS: Nausea, weakness, loss of appetite, vomiting within one hour with 100% incidence. Mild diarrhoea in less than 10% of exposed persons with an onset of 3 to 8 hours following the whole body exposure. Headache in 50% of the exposed persons within 4 to 24 hours. Fever in 80–100% cases within 1 to 2 hours. Drop of lymphocytes to about 500 on 2^{nd}–3^{rd} day. Latent period of 1 to 2 weeks followed by severe clinical picture, fever, infections (pneumonia). Death in 50–80% of patients within 2 months.

>8 Sv : Lethal ARS: Severe nausea, fatigue and vomiting within 10 minutes followed by fever and diarrhoea and haemorrhage with no latent period. Rate of survival is very poor and death occurs within 2 weeks in 90–100% of exposed individuals. At whole body doses >15 Sv damage on the central nervous system characterized by cramps, involuntary movements of the muscles (ataxia) followed by coma (lethargy). Death occurs within 2 days due to irreversible circulatory cerebral odema and probably heart failure.

In case of protracted or low dose exposure, ionizing radiation may not produce immediate consequences but some delayed effects may appear a long time after the exposure. These types of effects may be late deterministic effects (life cataract) or stochastic effects (radiation induced cancer or genetic effects).

Genetic effects may be explained in the following way. It is a fact that children inherit characteristics such as appearance, strength, resistance to disease, temperament,, etc. from their parents. This happens because each of the parents contributes a characteristic gene to the reproduction process. The genes are contained in the sperm and egg cells of the parents producing them. Radiation can modify and damage the genes. However, genetic effects have never been manifested and proved in exposed to radiation human population groups (neither in A-bomb survivors).

In accordance with the recommendations of the International Commission on Radiological Protection, (ICRP), the dose limit of ionizing radiation is that, which in the light of present knowledge and in the opinion of competent medical authority, is not expected to cause injury to a person at any time during his lifetime and carries negligible probability of cancer induction and genetic malformations.

(1) Occupational workers

As per Schedule II of IAEA Safety Series No. 115, following criteria and dose limits apply:

II-5. The occupational exposure of any worker shall be so controlled that the following limits be not exceeded:

(a) an effective dose of 20 mSv per year averaged over five consecutive years;
(b) an effective dose of 50 mSv in any single year;
(c) an equivalent dose to the lens of the eye of 150 mSv in a year; and
(d) an equivalent dose to the extremities (hands and feet) or the skin of 500 mSv in a year.

II-6: For apprentices of 16 to 18 years of age who are training for employment involving exposure to radiation and for students of age 16 to 18 who are required to use sources in the course of their studies, the occupational exposure shall be so controlled that the following limits be not exceeded:

(a) an effective dose of 6 mSv in a year;
(b) an equivalent dose to the lens of the eye of 50 mSv in a year; and
(c) an equivalent dose to the extremities or the skin of 150 mSv in a year.

II-7: When, in special circumstances, a temporary change in the dose limitation requirements is approved pursuant to Appendix I:

(a) the dose averaging period mentioned in para. II-5 (a) may exceptionally be up to 10 consecutive years as specified by the regulatory authority, and the effective dose for any worker shall not exceed 20 mSv per year averaged over this period and shall not exceed 50 mSv in any single year, and the circumstances shall be reviewed when the dose accumulated by any worker since the start of the extended averaging period reaches 100 mSv; or

(b) the temporary change in the dose limitation shall be as specified by the regulatory authority but shall not exceed 50 mSv in any year and the period of the temporary change shall not exceed 5 years.

The occupational dose constrain for the whole body exposures in forty years of working lifetime of an individual is 1 Sv. The maximum accumulated dose to a radiation worker of age N years is given by (N-18) × 20 mSv. This means that no person less than 18 years of age can be employed for radiation work.

Radiation workers such as radiographers are subjected to ionizing radiation while performing their work. The amount of radiation dose received depends on various parameters and conditions such as time, distance, shielding and working procedure. Thus, to ensure the safety of radiographers, it is important that supervisors or radiation protection officers continuously observe and record the amount of radiation received by each radiographer working under them. Such an activity is called personnel monitoring.

In general, the main purposes of personnel monitoring are to ensure that the dose limit is not exceeded, to limit the exposure of the individual radiographer, to assist the medical authority in making analysis in the case of accidental over exposure and to provide information about work practices and personal dose history. The other type of monitoring is area monitoring in which the environment around the worker is monitored. This includes checking the equipment containing radioactive sources, and the correctness of the exposure procedures. Personnel monitoring devices include film badges, pocket dosimeters and thermoluminescence dosimeters (TLD), while the area monitoring is done with the help of radiation survey meters.

(2) Non-occupational workers

For all non-occupational workers and members of the public being exposed to external radiation, the above mentioned dose limits must be reduced appreciably to keep limited the spread of radiation effects if any. The criteria and dose limits specified by Schedule II of IAEA Safety Series No. 15 for this category of personnel are as given below:

II-8: The estimated average doses to the relevant critical groups of members of the public that are attributable to practices shall not exceed the following limits:

(a) an effective dose of 1 mSv in a year;
(b) in special circumstances, an effective dose of up to 5 mSv in a single year provided that the average dose over five consecutive years does not exceed 1mSv per year;
(c) an equivalent dose to the lens of the eye of 15 mSv in a year; and
(d) an equivalent dose to the skin of 50 mSv in a year.

3.5.5 Applications of radiographic testing method

Radiographic testing is mainly applied for the detection of flaws such as cracks, porosity, inclusions, lack of root penetration, lack of fusion, laps, seams, shrinkage, corrosion, etc. in weldments and castings, in pressure vessels, containers for industrial liquids and gases, pipelines, steel bridges, steel and aluminium columns and frames and roofs, nuclear reactors and nuclear fuel cycle, boiler tubes, ships and submarines, aircraft and armaments. In most of these cases weld inspection is involved. Welds in plates are tested using an arrangement more or less similar to the one shown in Figure 3.11. However, there are a number of different techniques for inspection of welds in pipes. These are illustrated in Figure 3.15. The welds in small diameter pipes are inspected usually using source-outside film-outside technique (Figure 3.15 (c, d)). Medium diameter pipes may also be inspected as in Figure 3.15 (b) where source-inside-film outside technique is utilised. When the diameter of pipes becomes large enough, the circular welds may be examined using a panoramic technique (Figure 3.15 (a)). In this the source is placed at the centre inside the pipe and the film is wrapped all around the weld on the outside. Thus in this case the whole weld can be radiographed in a single

exposure while for all other situations in Figure 3.15 multiple exposures are required for full coverage.

Radiography is also extensively used for the inspection of castings and forgings. The regular shaped and uniformly thick specimens can be inspected as usual like welds in plates while special considerations need to be made for testing of specimens of varying thickness. Double film technique is usually employed wherein two films of different speeds are used for a single exposure. In this way correct density is obtained under the thick sections on the faster film whereas the slower films record correct images of the thin sections.

Radiography is used in inspection of explosives contained within casings, sealed boxes and equipment. In the field of electronics it is employed for the inspection of printed circuit boards and assemblies for checking adequacy of connections.

The special forms of radiographic testing have in fact been developed for the purposes of some specialized applications which are mentioned under each technique in Section 3.5.3.

3.5.6 Range and limitations of radiographic testing

Radiographic testing method is generally applicable for the inspection of all types of materials, e.g. metallic, non-metallic and plastics, magnetic and non-magnetic, conductors and non-conductors, etc. as long as both sides of the test specimen are accessible for placement of source and the film on either side. The film needs to be placed in contact with the specimen and whenever this is not possible due to the geometry of the test specimen, radiographs of poorer quality will result.

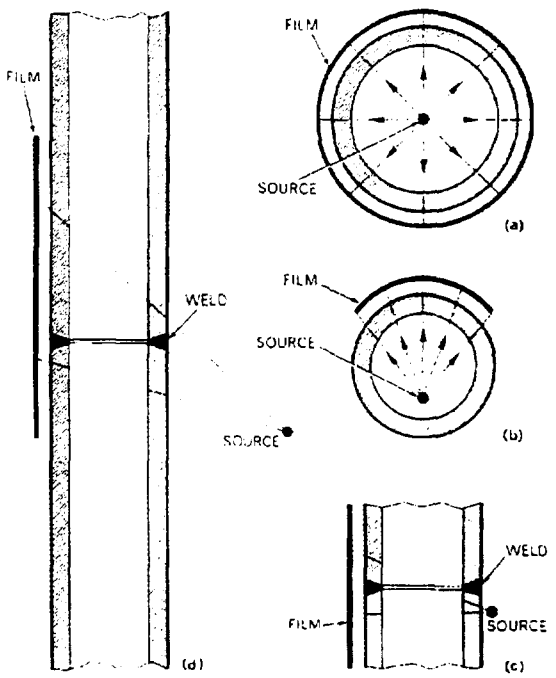


Figure 3.15 : Various techniques for weld inspection.

The penetration of the radiation through the test specimen depends upon its thickness and density. For high density materials, as well as for larger thickness of the same material, higher energies are needed. Although, in principle, these higher energies are now available from betatrons and linear accelerators, these sources of radiation are extremely expensive and therefore not available for common use. Table 3.1 shows that among the commonly available radiation sources including the commercial X ray machines of up to about 420 KV, the strongest source is that of cobalt-60 which can be used for radiography of steel of thickness up to about 150 mm.

The factors affecting radiographic quality and consequently the sensitivity of flaw detection by radiographic testing method need to be carefully considered while selecting the technique for a particular test. For example, for high sensitivity or to be able to detect smaller flaws, it is recommended that largest possible source-to film distance is used with a source of the smallest possible dimensions, the slowest and fine-grained film should be used and film processing should be done as per recommendations of the manufactures (usually for 5 minutes at 20°C). The lowest energy compatible with the thickness and density of the test specimen should be chosen. In practice a compromise has to be made between these ideal requirements to achieve an optimum level of sensitivity. But a radiograph made with a technique of poor sensitivity will need a more critical inspection, since defect images will not be so easily seen and may in fact be missed. There is a definite tendency to make a more cursory examination when defect images are only faintly seen. Similarly very small defects below the sensitivity limits of the technique employed may be missed. Such a situation can also arise due to improper viewing conditions and the training and experience of the interpreter. Sensitivity of flaw detection decreases with an increase in thickness of the test specimen.

Radiographic picture is a two-dimensional shadow of a three-dimensional defect. The orientation of the defect with respect to the direction of the beam is therefore an important consideration. Thus planar defects such as cracks, laminations, lack of fusion in welds or similar defects may not be detected if their plane is at right angles to the incident beam. Elongated defects like pipes and wormholes may show up and be misinterpreted as spherical defects. Smaller defects located behind the larger ones in the direction of the beam will not be detected.

A serious limitation with the radioisotope sources used for radiography is the fact that even unused their activity decreases with time. While they have the distinct advantage of needing no power for field radiography applications, they need special shielded enclosures to house them and the radiographic sensitivity achievable with them is usually inferior to that for X rays.

Lastly, exposure to radiations can be dangerous for human health and therefore special precautions are required which may include construction of specially shielded enclosures and cordoning off of the area where radiography is being performed. Mostly it involves either stopping of all other work and removal of the workers from the work place while carrying out radiography or to do the radiographic testing work during off hours.

3.6 ULTRASONIC TESTING

3.6.1 Fundamental principles

3.6.1.1 Nature and type of ultrasonic waves

Ultrasonic inspection is a non-destructive testing method in which high frequency sound waves are introduced into the material being inspected and the sound emerging out of the test specimen is detected and analysed. Most ultrasonic inspection is done at frequencies between 0.5 and 25 MHz well above the range of human hearing, which is about 20 Hz to 20 kHz. Ultrasonic waves are mechanical vibrations of the particles of the medium in which they travel. The waves are represented by a sinusoidal wave equation having a certain amplitude, frequency and velocity. Amplitude is the displacement of the particles of the medium from their mean position. Frequency is the number of cycles per second and the length of one cycle is called wavelength. The relationship between frequency, wavelength and velocity is given by $v = \lambda f$ where v is the velocity of a wave (in a medium) having frequency f and wavelength λ .

Each medium through which sound waves travel is characterized by an acoustic impedance denoted by 'Z' which is the resistance offered by the medium to the passage of sound through it. Since the values of Z are different for different materials the velocity of sound waves is different in different materials. Velocity also depends upon the elastic properties of the medium and is given by $v \cong (q/\rho)^{1/2}$ where q is the modulus of elasticity and ρ is the density. Also $Z = \rho v$.

There are two main types of ultrasonic waves. Longitudinal waves or compressional waves are those in which alternate compression and rarefaction zones are produced by the vibration of the particles. The direction of oscillation of the particles .is parallel to the direction of propagation of the waves. Because of its easy generation and detection, this type of ultrasonic wave is most widely used in ultrasonic testing. Almost all of the ultrasonic energy used for the testing of materials originates in this mode and is then converted to other modes for special test applications. This type of wave can propagate in solids, liquids and gases. In transverse or shear waves the direction of particle displacement is at right angles to the direction of propagation. For all practical purposes, transverse waves can only propagate in solids. This is because the distance between molecules or atoms, the mean free path, is so great in liquids and gases that the attraction between them is not sufficient to allow one of them to move the other more than a fraction of its own movement and so the waves are rapidly attenuated. In a particular medium the velocity of transverse waves is about half that of the longitudinal waves. Table 3.2 gives the comparative velocities in some common materials.

3.6.1.2 Reflection and transmission of sound waves

Sound energy may be reflected, refracted, scattered, absorbed or transmitted while interacting with a material. Reflection takes place in the same way as for light, i.e. angle of incidence equals angle of reflection. At any interface between two media of different acoustic impedances a mismatch occurs causing the major percentage

TABLE 3.2 : VELOCITIES OF SOUND IN SOME COMMON MATERIALS ($X10^5 cm\ s^{-1}$)

Material	Longitudinal	Transverse
Aluminium	6.32	3.13
Brass	4.28	2.03
Copper	4.66	2.26
Gold	3.24	1.20
Iron	5.90	3.23
Lead	2.16	0.70
Steel	5.89	3.24
Perspex	2.70	1.40
Water	1.43	-
Oil (transformer)	1.39	-
Air	0.33	-

of the wave to be reflected back, the remainder being transmitted. There are two main cases:

3.6.1.2.1 Reflection and transmission at normal incidence

The percentage of incident energy reflected from the interface between two materials depends on the ratio of acoustic impedances of the two materials and the angle of incidence. When the angle of incidence is 0 (normal incidence), the reflection coefficient (R), which is the ratio of the reflected beam intensity I_r to the incident beam intensity I_i, is given by

$$R = I_r/I_i = (Z_2 - Z_1)^2 / (Z_2 + Z_1)^2$$

where Z_1 is the acoustic impedance of medium 1, and Z_2 is the acoustic impedance of medium 2. The remainder of the energy is transmitted across the interface into the second material. The transmission coefficient (T) which is the ratio of the transmitted intensity 'I_t' to the incident intensity 'I_i' is given by

$$T = I_r/I_t = Z_1, Z_2/(Z_1+Z_2)^2$$

Using the values of characteristic impedances, reflection and transmission coefficients can be calculated for pairs of different materials. The equations show that the transmission coefficient approaches unity and the reflection coefficient tends to zero when Z_1 and Z_2 have approximately similar values. The materials are then said to be well matched or coupled. On the other hand, when the two materials have substantially dissimilar characteristic impedances, e.g. for a solid or liquid in contact with a gas, the transmission and reflection coefficients tend to zero and 100 per cent prospectively. The materials are then said to be mismatched or poorly coupled. It is for this reason that a coupling fluid is commonly used when transmitting or receiving sound waves in solids.

3.6.1.2.2 Reflection and transmission at oblique incidence

When an ultrasonic wave is incident on the boundary of two materials at an angle other than normal, the phenomenon of mode conversion (a change in the nature of the wave motion i.e. longitudinal to transverse and vice versa) must be considered. All possible ultrasonic waves leaving the point of impingement are shown for an incident longitudinal ultrasonic wave in Figure 3.16. Mode conversion can also take place on the reflection side of the interface if material 1 is solid.

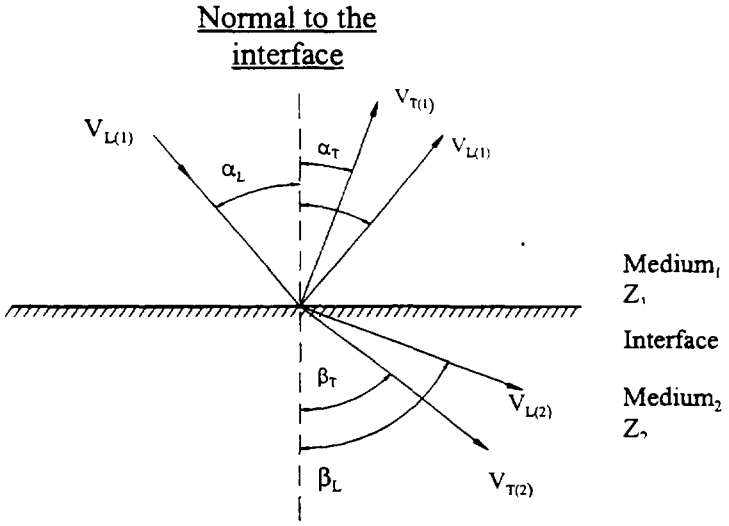


Figure 3.16 : Phenomena of reflection, refraction and mode conversion for an incident wave.

where

$v_{L(1)}$ and $v_{L(2)}$ = velocities of longitudinal waves in material 1 and 2 respectively.

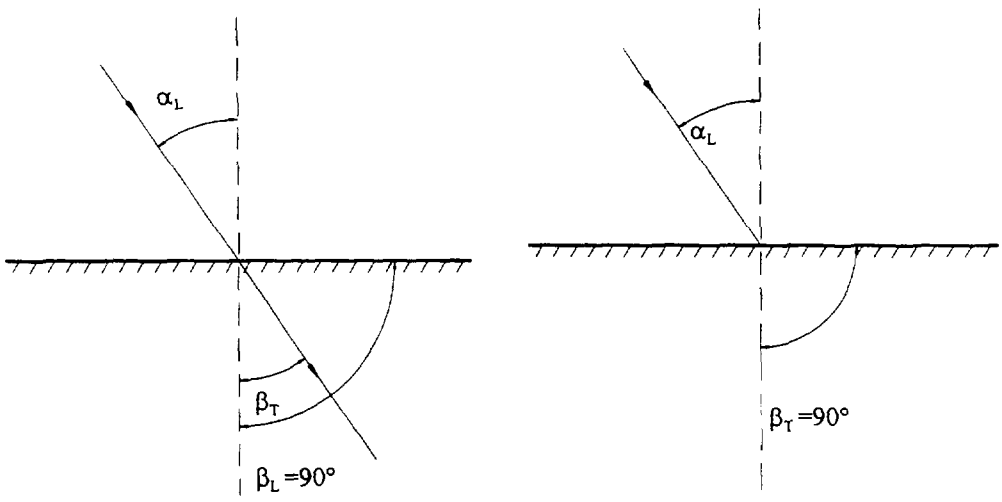
$v_{T(1)}$ and $v_{T(2)}$ = velocities of transverse waves in material 1 and 2 respectively.

α_L and α_T = angles of reflection of longitudinal wave and transverse wave respectively in material 1.

β_L and β_T = angles of refraction of longitudinal wave and transverse wave respectively in material 2.

3.6.1.2.3 First and second critical angles

If the angle of incidence α_L is small (Figure 3.17), ultrasonic waves travelling in a medium undergo the phenomena of mode conversion and refraction on encountering a boundary with another medium. This results in the simultaneous propagation of longitudinal and transverse waves at different angles of refraction in the second medium. As the angle of incidence is increased, the angle of refraction also increases. When the refraction angle of a longitudinal wave reaches 90° the wave emerges from the second medium and travels parallel to the boundary (Figure 3.17a). The angle of incidence at which the refracted longitudinal wave emerges is called the first critical angle. If the angle of incidence α_L is further increased the angle of refraction for the transverse wave also approaches 90°. The value of α_L (Figure 3.17b) for which the angle of refraction of the transverse wave is exactly 90° is called the second critical. angle At the second critical angle the refracted transverse wave emerges from the medium and travels parallel to the boundary. The transverse wave has thus become a surface or Raleigh wave.



a) First critical angle b) Second critical angle

Figure 3.17 : First and second critical angles.

3.6.2 Equipment for ultrasonic testing

The equipment for ultrasonic testing mainly consists of a flaw detector, transducers and the test or calibration blocks. These are briefly described here. Figure 3.18 shows the block diagram for a typical flaw detector. A pulse generator generates pulses of alternating voltages which excite the crystal in the probe to generate specimen by coupling the probe to it. The waves are reflected from the far boundary of the test specimen or from any discontinuities within it and reach the probe again. Here through the reverse piezoelectric effect the ultrasonic waves are converted into voltage pulses and are fed to the y-plates of a cathode ray tube through an amplifier. These then are displayed on the CRT screen as pulses of definite amplitude and can be interpreted as signals from the back wall of the test specimen or from the discontinuity present within it.

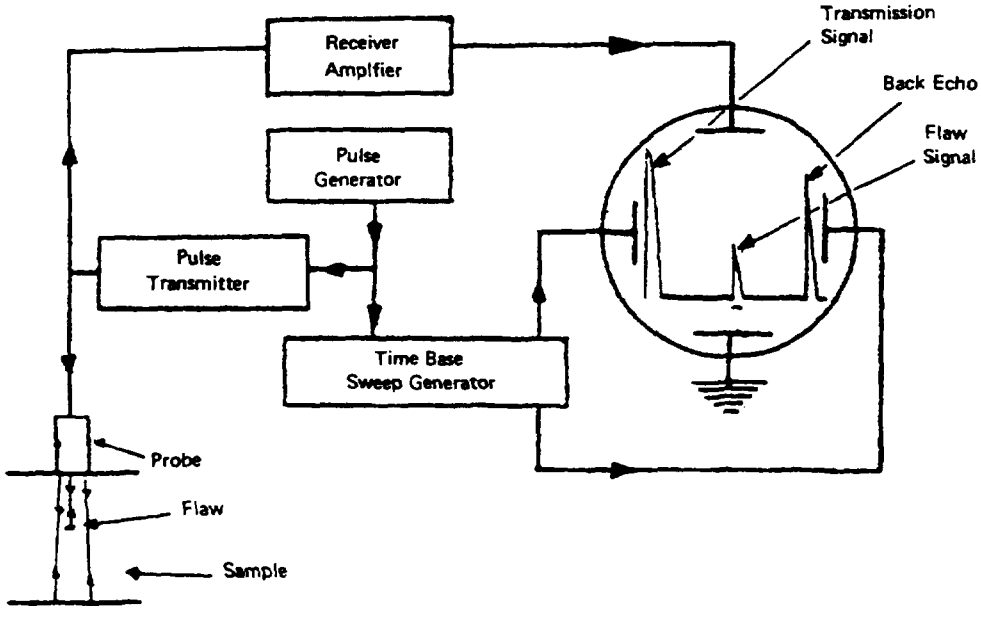


Figure 3.18 : A typical ultrasonic test unit.

Ultrasound is generated in certain natural and artificially made crystals which show the effect of piezoelectricity i.e. they produce electric charges on being subjected to mechanical stresses and vice versa. Thus on the application of electric pulses of appropriate frequency these crystals produce ultrasonic pulses which are mechanical vibrations. The most commonly used materials are quartz, lithium sulphate, barium titanate and lead metaniobate. The properly cut crystal is contained in a housing, the whole assembly being termed as an ultrasonic probe. The two faces of the crystal are provided with electrical connections. On the front face of the crystal (the face which comes in contact with the test specimen) a perspex piece is provided to avoid wear and tear of the crystal. At the rear of the crystal there is damping material such as a spring or tungsten araldite. This damping material is necessary to reduce the vibration of the crystal after transmitting the ultrasonic pulse so that the crystal can be more efficient as a receiver of sound energy. Damping is necessary therefore to improve the resolution of the probe. A typical probe is shown in Figure 3.19. The probe generates ultrasound of a particular frequency which depends upon the thickness of the piezoelectric crystal. The sound comes out of the probe in the form of a cone-like beam which has two distinct regions namely the near field and the far field. Most of the testing is performed using the far field region of the beam. The probes that send the ultrasonic beams into the test specimen at right angles to the surface are called normal beam probes while those that send beams into the specimen at a certain angle are termed as angle beam probes. In angle beam probes the crystal is mounted on a perspex wedge so that the longitudinal waves fall on the surface of the test specimen obliquely. Then through the phenomenon of mode conversion and choosing a suitable angle of incidence, shear waves can be sent into the test specimen at the desired angle. These angle beam probes are used specially for the inspection of welds whose bead has not been removed.

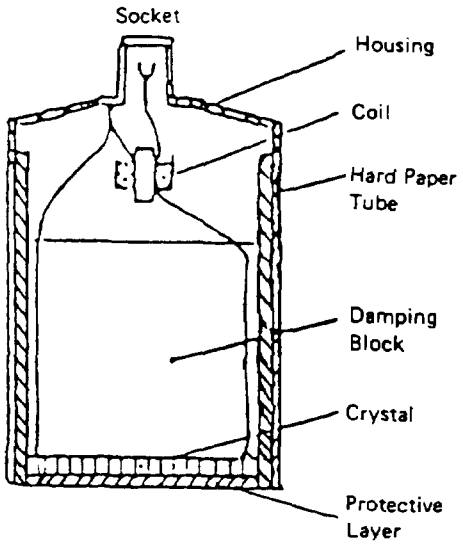


Figure 3.19 : A typical normal beam single crystal ultrasonic probe.

To draw any meaningful conclusions from the indications of reflected ultrasound the flaw detector-probe system should be properly calibrated using standard calibration blocks. There is a large variety of these blocks which are in use for

different types of inspection problems. Some of the most commonly used ones are briefly described here. The I.I.W test block, shown in Figure 3.20, can be used to set test sensitivity, time base calibration, determination of shear wave probe index and angle, checking the amplifier linearity and checking the flaw detector - probe resolving power. The block is sometimes referred to as the V1 block.

The V2 test block is mainly used with the miniature angle probes to calibrate the CRT screen. The block is shown in Figure 3.21 along with the CRT screen appearance when the probe is placed in two different positions on the block.

Some blocks are made having flat bottom holes. These type of test blocks are made from a plate of the same material as the material under test. The ASTM area-amplitude blocks and distance-amplitude blocks are examples of this type of block (Figure 3.22).

These blocks provide known-area reflectors which can be compared to reflections from unknown reflectors. They also enable reproducible levels of sensitivity to be set and therefore to approximate the magnitude of flaws in terms of reflectivity. In addition to the standard test blocks there are a number of other test blocks available. In general a test block should simulate the physical and metallurgical properties of the specimen under test. The variety of test blocks available can be found by consulting the various national standards, e.g. ASME, ASTM, BS, DIN, JIS, etc.

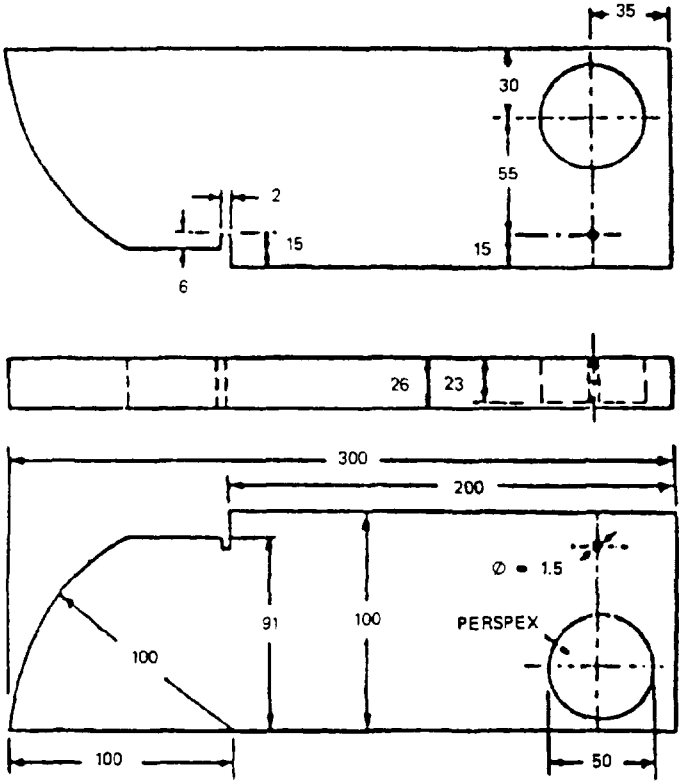


Figure 3.20 : I.I.W test block.

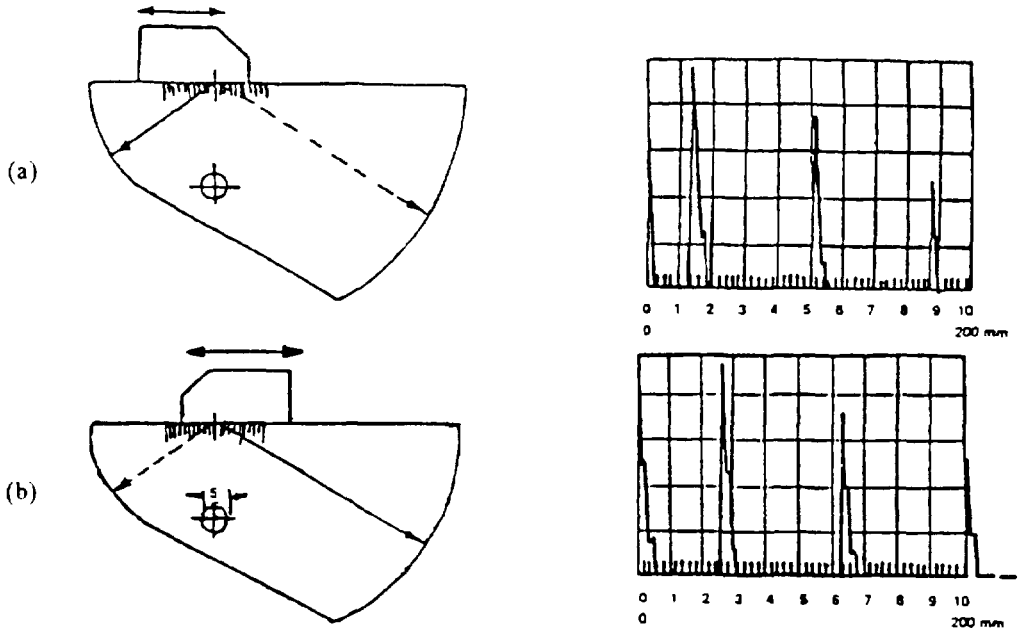


Figure 3.21 : V2 test block (a) with the probe index at the zero point and directed to the 25 mm radius, (b) with the probe index at the zero point and directed to the 50 mm radius.

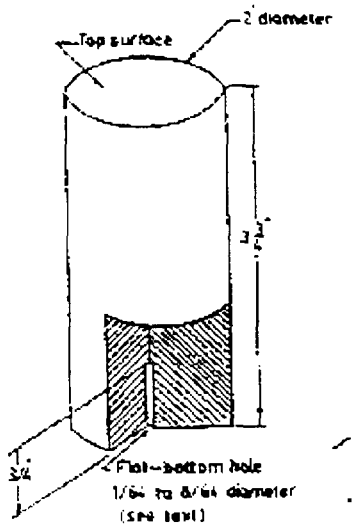


Figure 3.22 : Flat bottom hole type test block.

3.6.3 General procedure for ultrasonic testing

The most commonly used method of ultrasonic testing is the pulse-echo or reflection method. In this case the transmitter and receiving probes are on the same side of the specimen and the presence of a defect is indicated by the reception of an echo before that of the boundary or backwall signal. The CRT screen shows the separation between the time of arrival of the defect echo

compared to that of the natural boundary of the specimen, therefore, location of the defect can be assessed accurately. Usually one probe acts simultaneously as a transmitter and then as a receiver and is referred to as a TR probe. The principle of the pulse echo method is illustrated in Figure 3.23.

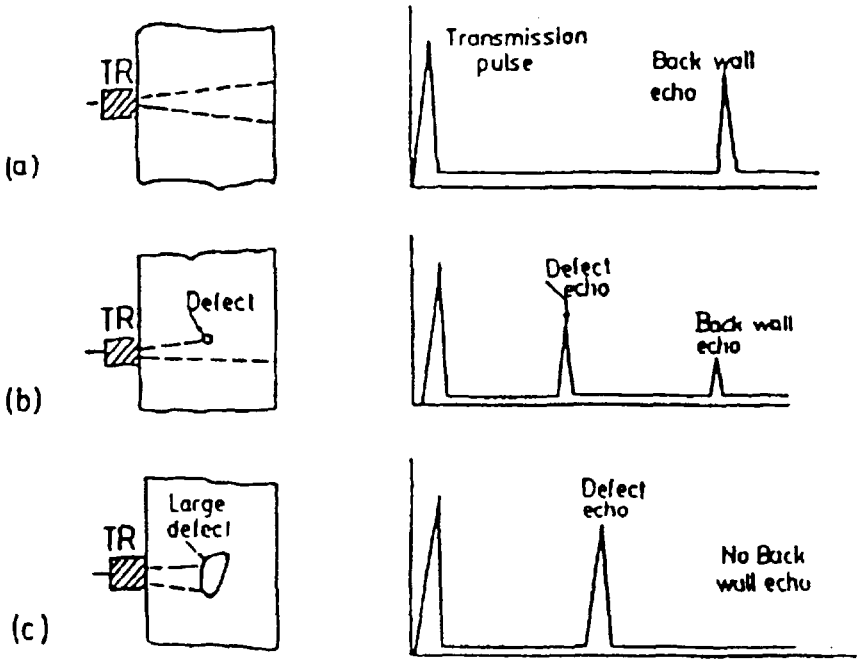


Figure 3.23 : Principle of pulse echo method of ultrasonic testing (a) defect free specimen (b) specimen with small defect (c) specimen with large defect.

The time base of the CRT can be calibrated either in units of time or, if the velocity of sound in the material is known, in units of distance. If "l" is the distance from the transducer to the defect and "t" the time taken for waves to travel this distance in both directions then, $l = vt/2$ where v is the sound velocity in the material.

The procedure to conduct an ultrasonic test is influenced by a number of factors. Also the nature of the test problems in industry varies over a wide range. Therefore it is difficult to define a method which is versatile enough to work in all situations. However, it is possible to outline a general procedure which will facilitate the inspection by ultrasonics in most cases.

(i) The test specimen

Specimen characteristics such as the condition and type of surface, the geometry and the microstructure are important. Very rough surfaces may have to be made smooth by grinding, etc. Grease, dirt and loose scale or paint should be removed. The geometry of the specimen should be known since this has a bearing on the reflection of sound inside the specimen. Some reflections due to a complex geometry may be confused with those from genuine defects. The material

microstructure or grain structure affects the degree of penetration of sound through it. For a fixed frequency the penetration is more in fine grained materials than in coarse grained materials.

(ii) Types of probes and equipment

The quality of ultrasonic trace depends on the probes and equipment which in turn determine the resolving power, the dead zone and the amount of sound penetration. It is difficult to construct a probe which will provide good detection and resolution qualities and at the same time provide deep penetration. For this reason, a variety of probes exist some of which are designed for special purposes. For the examination of large surface areas it is best to use probes with large transducers in order to reduce the time taken for the test. However the wide beam from such a probe will not detect a given size of flaw as easily as a narrower one. The probability of detecting flaws close to the surface depends on the type of equipment and probes used. The dead zone can be decreased in size by suitably designing the probe and also shortening the pulse length. The selection of the test frequency must depend upon previous experience or on preliminary experimental tests or on code requirements. The finer the grain structure is, the greater is the homogeneity of the material and the higher is the frequency which can be applied. The smaller the defects being looked for the higher the frequency used. Low frequencies are selected for coarse grained materials such as castings, etc. After the selection of the probe and the equipment has been finalized, its characteristics should be checked with the help of test blocks.

(iii) Nature of defects

Defect characteristics which include the type, size and location, differ in different types of materials. They are a function of the design, manufacturing process and the service conditions of the material. The detection and evaluation of large defects is not normally a difficult problem. The outline of a defect can be obtained approximately by moving the probe over the surface of the test specimen. The flaw echo increases from zero to a maximum value as the probe is moved from a region free from defects to a point where it is closest to a defect. Information as to the character of a defect can be obtained from the shape of the defect echo. For small defects, the size of the defect is estimated by comparing the flaw reflectivity with the reflectivity of standard reflectors. If the standard reflector is of the same shape and size as the unknown flaw, the reflectivity will be the same at the same beam path length. Unfortunately this is seldom the case since reference reflectors are generally flat bottomed holes or side drilled holes and have no real equivalence to real flaws. Theoretically it is possible under favourable conditions to detect flaws having dimensions of the order of half a wavelength. Indications obtained with an ultrasonic flaw detector depend to a great extent on the orientation of the defect in the material. Using the single probe method, the largest echoes are obtained when the beam strikes the surface of the specimen at right angles. On a properly calibrated time base the position of the echo from a defect indicates its location within the specimen. The determination of the type, size and location of defects which are not at right angles to the sound beam is complicated and needs deep understanding and considerable experience.

(iv) Selection of couplant

The couplant provides impedance matching between the probe and the test specimen. The degree of acoustic coupling depends on the roughness of the surface and the type of couplant used. In general the smoother the surface the better the conditions for the penetration of ultrasonic waves into the material under test. Commonly used couplants are water, oils of varying degrees of viscosity, grease, glycerine and a mixture of 1 part glycerine to 2 parts water. Special pastes such as Polycell mixed with water are also used.

(v) Test standards

Standards are used to check the performance of the flaw detector probe system. There are mainly two types of these standards. The first type of standard is used to control such parameters as amplifier gain, pulse power and time base marking and to ensure that they remain constant for the whole of the test. They are also used to verify the angle of incidence and to find the point where the beam emerges in angle probes. Another purpose of this group of standards is to calibrate the time base of the oscilloscope. The second group of standards contains those used for special purposes. They are normally used for tests which are largely dependent on the properties of the examined material and, if possible, they are made of the same materials and have the same shapes as the examined objects. These standards allow for the setting of the minimum permissible defect as well as the location of defects.

(vi) Scanning procedure

Before undertaking an ultrasonic examination, the scanning procedure should be laid down. For longitudinal probes this is simple but care must be taken with angle or shear wave probes. For instance in the inspection of welds using an angle probe scanning begins with the probe at either the half skip or full skip positions and continues with the probe being moved in a zigzag manner between the half skip and full skip positions. There are in general four scanning movements in manual scanning, rotational, orbital, lateral and traversing. The half skip position is recommended for critical flaw assessment and size estimation whenever possible. In some special applications the gap scanning method is employed. Here, an irrigated probe is held slightly away from the material surface by housing it in a recess made in a contact scanning head. Probe wear can be avoided by interposing a free running endless belt of plastic ribbon between the probe and the test surface. Acoustical coupling is obtained by enclosing the probe in an oil filled rotating cylinder in which case only the surface requires irrigation. Immersion scanning, which is most commonly used in automatic inspection, is done by holding the probe under water in a mechanical or electronic manipulator, the movement of which controls the movement of the probe.

(vii) Defect sizing

After the flaws in the test specimen have been detected it is important to evaluate them in terms of their type, size and location. Whereas the type and location of the flaw may be inferred directly from the echo on the CRT screen; the size of the flaw

has to be determined. The commonly used methods for flaw sizing in ultrasonic testing are 6 dB drop method, 20 dB drop method, maximum amplitude method and the DGS diagram method. The basic assumption in the 6 dB drop method is that the echo height displayed when the probe is positioned for maximum response from the flaw will fall by one half (i.e. by 6 dB and hence the name) when the axis of the beam is brought in line with the edge of the flaw. The method only works if the ultrasonic response from the flaw is essentially uniform over the whole reflecting surface. If the reflectivity of the flaw varies considerably the probe is moved until the last significant echo peak is observed just before the echo drops off rapidly. This peak is brought to full screen height and then the probe is moved to the 6 dB point as before. A similar procedure is followed for the other end of the flaw. The 6 dB drop method is suitable for the sizing of flaws which have sizes of the same order or greater than that of the ultrasonic beam width but will give inaccurate results with flaws of smaller sizes than the ultrasonic beam. It is therefore generally used to determine flaw length but not flaw height. The 20 dB drop method utilizes for the determination of flaw size, the edge of the ultrasonic beam where the intensity falls to 10% (i.e. 20 dB) of the intensity at the central axis of the beam. The 20 dB drop method gives more accurate results than the 6 dB drop method because of the greater control one has on the manipulation of the ultrasonic beam. However, size estimation using either the 6 dB or 20 dB drop method have inherent difficulties which must be considered. The main problem is that the amplitude may drop for reasons other than the beam scanning past the end of the defect due to any of the following reasons:

(a) The defect may taper in section giving a reduction in cross sectional area within the beam. If this is enough to drop the signal 20 dB or 6 dB the defect may be reported as finished while it in fact continues for an additional distance.

(b) The orientation of the defect may change so that the probe angle is no longer giving maximum response, another probe may have to be used.

(c) The defect may change its direction.

(d) The probe may be twisted inadvertently.

(e) The surface roughness may change.

The maximum amplitude method takes into account the fact that most defects which occur do not present a single, polished reflecting surface, but in fact take a rather ragged path through the material with some facets of the defect surface suitably oriented to the beam and some unfavourably oriented. As the beam is scanned across the surface of the defect, the beam centre will sweep each facet in turn. As it does, the echo from that facet will reach a maximum and then begin to fall, even though the main envelope may at any instant, be rising or falling in echo amplitude. The stand-off and range of the maximum echo of each facet is noted and plotted on the flaw location slide. This results in a series of points which trace out the extent of the defect. The gain is increased to follow the series of maximum echoes until the beam sweeps the last facet.

The DGS method makes use of the so called DGS diagram, developed by Krautkramer in 1958 by comparing the echoes from small reflectors, namely different diameter flat bottom holes located at various distances from the probe, with the echo of a large reflector, a back wall reflector, also at different distances from the probe (Section 7.2.4). For normal probes it relates the distance D from the probe (i.e. along the beam) in near field units, thus compensating for probes of different sizes and frequencies, to the gain G in dB for a flat bottom hole compared to a particular back wall reflector and the size S of the flat bottom hole as a proportion of the probe crystal diameter.

Since in the case of angle beam probes some of the near field length is contained within the perspex path length and this varies for different designs and sizes of probe, individual DGS diagrams are drawn for each design, size and frequency of angle beam probe. For this reason the scale used in the D-scale is calibrated in beam path lengths, the G-scale in decibels as before and the S-scale representing flat bottom hole or disc shaped reflector diameters in mm.

(viii) Test report

In order that the results of the ultrasonic examination may be fully assessed it is necessary for the tester's findings to be systematically recorded. The report should contain details of the work under inspection, the code used, the equipment used and the calibration and scanning procedures. Also the probe angles, probe positions, flaw ranges and amplitude should be recorded in case the inspection needs to be repeated. The principle is that all the information necessary to duplicate the inspection has to be recorded (Section 7.5).

3.6.4 Applications of ultrasonic testing

3.6.4.1 Thickness measurements

Thickness measurements using ultrasonics can be applied using either the pulse echo or resonance techniques. Some typical applications are:

(i) Wall thickness measurement in pressure vessels, pipelines, gas holders, storage tanks for chemicals and accurate estimate of the effect of wear and corrosion without having to dismantle the plant.

(ii) Measurement of the thickness of ship hulls for corrosion control.

(iii) Control of machining operations, such as final grinding of hollow propellers.

(iv) Ultrasonic thickness gauging of materials during manufacture.

(v) Measurement of wall thickness of hollow aluminium extrusions.

(vi) Measurement of the thickness of lead sheath and insulating material extruded over a core of wire.

(vii) Inspection of heat exchanger tubing in nuclear reactors.

(viii) Measurement of the wall thickness of small bore tubing including the canning tubes for reactor fuel elements.

3.6.4.2 Flaw detection

Typical flaws encountered in industrial materials are cracks, porosity, laminations, inclusions, lack of root penetration, lack of fusion, cavities, laps, seams, corrosion, etc. Some examples of the detection of these defects are as follows:

(i) Examination of welded joints in pressure vessels, containers for industrial liquids and gases, pipelines, steel bridges, pipelines, steel or aluminium columns, frames and roofs (during manufacturing, pre-service and in-service).

(ii) Inspection of steel, aluminium and other castings.

(iii) Inspection of rolled billets, bars and sections.

(iv) Inspection of small bore tubes including the canning tubes for nuclear fuel elements.

(v) Ultrasonic testing of alloy steel forgings for large turbine rotors.

(vi) Testing of turbine rotors and blades for aircraft engines.

(vii) Early stage inspection in the production of steel and aluminium blocks and slabs, plates, bar sections, tubes, sheets and wires.

(viii) Detection of unbonded surfaces in ceramics, refractories, rubber, plastics and laminates.

(ix) Detection of honeycomb bond in the aircraft industry.

(x) Inspection of jet engine rotors.

(xi) Detection of caustic embrittlement failure in riveted boiler drums in the power generation industry.

(xii) Detection of cracks in the fish plate holes in railway lines and in locomotive and bogey axles.

(xiii) Detection of hydrogen cracks in roller bearings resulting from improper heat treatment.

(xiv) In service automatic monitoring of fatigue crack growth.

(xv) Detection of stress corrosion cracking.

(xvi) Detection of fatigue cracks in parts working under fluctuating stress.

(xvii) Inspection of fine quality wire.

(xviii)Testing of wooden components such as utility poles.

(xix) Application of ultrasonics to monitor material characteristics in the space environment.

(xx) Determination of lack of bonding in clad fuel elements.

(xxi) Detection of flaws in grinding wheels.

(xxii) Varieties of glass which are not sufficiently transparent to allow optical inspection can be tested ultrasonically.

(xxiii)Quality control in the manufacture of rubber tyres by locating voids, etc.

(xxiv)Inspection of engine crankshafts.

3.6.4.3 Miscellaneous applications

In addition to the applications already mentioned there are numerous others. Notable among these are those based on the measurement of acoustic velocity and the attenuation of acoustic energy in materials. Some of these applications are as follows:

(1) Assessment of the density and tensile strength of ceramic products such as high tension porcelain insulators.

(2) Determination of the difference between various types of alloys.

(3) Detection of grain growth due to excessive heating.

(4) Estimation of the values of the elastic moduli of metals over a wide range of temperature and stress.

(5) Tensile strength of high grade cast iron can be estimated by measuring its coefficient of acoustical damping.

(6) Crushing strength of concrete can be measured from the transit time of an ultrasonic pulse.

(7) Quarrying can be made more efficient by the measurement of pulse velocity or attenuation in rock strata.

(8) To find the nature of formations in geophysical surveys without having to undertake boring operations.

(9) Detection of bore hole eccentricity in the exploration for mineral ores and oil.

(10) Study of press fits.

(11) Metallurgical structure analysis and control of case depth and hardness, precipitation of alloy constituents and grain refinement.

(12) Determination of intensity and direction of residual stresses in structural metal components.

(13) Detection of honeycomb debonds and the regions in which the adhesive fails to develop its nominal strength in the aerospace industry.

(14) Measurement of liquid level of industrial liquids in containers.

3.6.5 Range and limitations of ultrasonic testing

Advantages

The principal advantages of ultrasonic inspection as compared to other methods for non-destructive inspection of metal parts are:

(a) Superior penetrating power which allows the detection of flaws deep in the part. Ultrasonic inspection is done routinely to depths of about 20 ft in the inspection of parts such as long steel shafts and rotor forgings.

(b) High sensitivity permitting the detection of extremely small flaws.

(c) Greater accuracy than other non-destructive methods in determining the position of internal flaws, estimating their size and characterizing their orientation, shape and nature.

(d) Only one surface needs to be accessible.

(e) Operation is electronic, which provides almost instantaneous indications of flaws. This makes the method suitable for immediate interpretation, automation, rapid scanning, on-line production monitoring and process control. With most systems, a permanent record of inspection results can be made for future reference.

(f) Volumetric scanning ability, enabling inspection of a volume of metal extending from the front surface to the back surface of a part.

(g) Is not hazardous to operators or to nearby personnel, and has no effect on equipment and materials in the vicinity.

(h) Portability.

Disadvantages

(a) Manual operation requires careful attention by experienced technicians.

(b) Extensive technical knowledge is required for the development of inspection procedures.

(c) Parts that are rough, irregular in shape, very small or thin, or not homogeneous are difficult to inspect.

(d) Discontinuities that are present in a shallow layer immediately beneath the surface may not be detectable.

(e) Couplants are needed to provide effective transfer of ultrasonic wave energy between transducers and parts being inspected.

(f) Reference standards are needed, both for calibrating the equipment and for characterizing flaws.

3.7 OTHER METHODS OF NDT

3.7.1 Acoustic emission

Whenever materials are stressed, acoustic signals arise from plastic deformation, fracture or phase changes. The deformations may cause initiation and propagation of cracks with their typical sound emissions. These ultrasonic emission rates and intensity can be correlated with the type of cracks and their rate of propagation. The signals from the test specimen may be detected using a piezoelectric transducer and analysed using various techniques such as comparative or differential analysis, analysis of emission count rate, amplitude-frequency spectrum analysis, differential signal arrival time measurement or wave form or total emission count.

Acoustic emission technique can be used for measurement of tensile and fatigue properties, weld properties and metallurgical properties. It can also be used for study of crack initiation and propagation, strain rate, friction, wear, spalling and erosion effects, martensitic phase transformation, stress corrosion and fatigue. Typical applications include fracture specimen, nuclear cryogenic and other pressure vessels, airframe and engine components and fluid systems, incipient failure detection in stressed structures, dynamic monitoring, welding and die forming and pressure testing. The limitations of the technique are that a physical contact and acoustic coupling with the test object is required. Poor acoustic channels, noise or temperature may affect the signals. High ductile materials yield poor signals. It is required that a signature catalogue be created for signal interpretation. For flaw location by triangulation method multiple probes and computer are required.

3.7.2 Thermal methods

The thermal radiation output from a heated surface, when measured, would be different from a defect-free area as compared to that from a defective area. It can be applied either to component and systems which operate at temperatures above ambient or those which can be non-destructively heated or cooled. Either the temperatures over the test surfaces may be directly measured or the isotherms (contours of equal temperature) may be drawn. This may be done either by direct contact in which thermally sensitive device or material is placed in physical and

thermal contact with the article under test or by the use of non-contact techniques that depend upon thermally generated electromagnetic energy radiated from the test object which at moderate temperatures is predominantly infrared. The thermal methods may be used for the detection of porosity and voids, segregations and depletions, thickness variations, surface chemistry and composition, measurement of coating thickness, metal sorting, study of P-N junctions in semiconductors, lack of bond and pressure vessel welds, etc.

The instruments and gadgets used for temperature measurements include radiometers, pyrometers, thermocouples, thermopiles, metal bolometers, thermisters and meltable materials. The thermographic equipment consists of paints, phosphors, coatings, treated papers, liquid crystals, infra-red film, etc. The resolution for flaws is however, poor specially for thicker specimens. Only the areas containing the flaws are indicated without telling anything about the nature of flaws. Fixturing for heating and cooling is required. Temperature variations of the order of 1°C are only detectable.

3.7.3 Microwave testing

Microwaves are electromagnetic radiations having frequencies in the 300 MHz and 300 gHz range corresponding to wavelengths of 1 m to 1 mm. Continuous or pulsed microwave radiations when directed at objects propagate according to internal state or structure of the part. Inside the material under test they are scattered, reflected or attenuated and are detected and measured on the other side with the help of microwave guide and transducer crystals.

Microwaves can be used for the detection of cracks, porosity, holes and debonds, inhomogeneity of materials, reinforced plastic structures, polyurethane foam, solid propellants and motor casings. The moisture content of dielectric materials can also be determined as microwaves of an appropriate wavelength are strongly absorbed and scattered by water molecules.

Although no surface contact is required but positioning and alignment of waveguide and detector is critical. The waveguide arrangement is usually quite complex. Thickness variations usually of the order of 25 mm can be detected while the spatial resolution of flaws depends upon the probe (Horn) size and the microwave wavelength. Metal backing is required for thickness and position gauging of non-metals. The microwaves are quite safe and without any hazard at the power levels usually used. Efficient coupling through air from antennas to the material is achieved. There is no material contamination problem caused by the coupling means. Microwaves readily propagate through air, so successive reflections are not obscured by the first one. An important limitation to the use of microwaves is their inability to penetrate deeply into conductors or metals. This means that non-metallic materials inside a metallic container cannot be inspected.

3.7.4 Computer tomography

Computer tomography is in principle similar to radiography except that after passing through the test specimen the radiations (X or gamma rays) are detected by an array of radiation detectors instead of a film. The beam of radiation is finely

collimated, the object is moved perpendicular to the array of detectors and thus thin slices of the object are successively seen. The attenuated radiation is digitally sampled by the detectors. Data are obtained by translating and rotating the object to provide many viewing angles. A computer mathematically reconstructs an image of the cross-section from the multiple-view data. Features are not superimposed in the CT image and a transparent, three dimensional image of the part and its internal features can be built by adding vertical part movement and special image processing software.

All types of materials can be inspected for internal defects such as cracks, porosity, voids, inclusions and shrinkages, etc. In-situ applications for diagnostic purposes are also possible. Dimensional measurement capability of the order of 0.1 mm and flaw resolution of the order of 0.25 mm can be achieved. The method can provide inspection results at a fast rate with a large throughput of tested parts.

However, computer tomography cannot be applied to large, thin plates. Access is needed to all the sides of the test object. Sometimes process-dependent artefacts occur. The method uses sources of radiations and therefore has accompanying radiation hazards.

3.7.5 Strain sensing

All real solid objects undergo changes in geometrical configuration when subjected to mechanical loads. Such loads are termed as stresses and the corresponding changes in configuration as strains. The body can also experience strains as a consequence of other changes in its physical state, such as a temperature change. The methodology by which the relation between stresses and corresponding strains is empirically studied is called experimental stress analysis, although, the emphasis is, in fact upon the determination of strain. The most generally used practical methods of strain sensing are brittle coatings, photoelastic coatings and resistance strain gauges. The use of brittle coatings is based on the principle that when strained only very slightly a brittle substance will crack along a direction normal to the direction of tensile strain. Coatings are formulated to crack at various values of strain, calibration being made on a standardized cantilever beam at the time of the test. It is assumed that under similar strain on the test structure, cracks will begin to appear in the coating when the strain threshold has been reached. The photoelastic coatings which are usually plastics are applied to the surface of the part to be inspected and illuminated with polarized light. When the coating is viewed through a second polarizing lens (analyser), interference fringes are seen, the pattern depending upon the type of light used and the relative orientation of the polarizer and analyser. From the observed fringes, the direction of the principal strains can be determined and their magnitudes, in principle, calculated.

Many strain-measuring methods utilise some means of converting strain information into an electric signal that is easily amplified and displayed. The conventional bonded resistance strain gauge consists of a wire or foil grid which, when cemented to the test structure, undergoes changes in electrical resistance in direct proportion to the changes in strain in the structure. Semiconductor strain gauges are usually made of a piezoresistive semiconductor material whose electric resistance is extremely sensitive to changes in strain. Resistance changes from

either type of gauge may be measured using a Wheatstone bridge arrangement or by amplifying a signal from the gauge and displaying it on conventional electric readout equipment

The strain sensing methods may be applied to metals, non-metals as well as composites for measurement of micro displacements, torques and pressures. They may also be applied for studies of creep and crack growth, for tensile testing, stress analysis and strain monitoring in stressed components and systems. In-situ strain measurements may be made in operating turbines, engines, airframes, ship hulls, cranes, earth-moving equipment and pressure vessels. The strain sensing devices have to be applied to cleaned and prepared surface with access to the critical area. These are affected by temperature, humidity and moisture. The gauges become bonded to the equipment and are therefore not available for use elsewhere.

3.7.6 Leak testing

It is conventional to use the term "leak" to refer to an actual discontinuity or passage through which a fluid flows or permeates. "Leakage" refers to the fluid that has flown through a leak. "Leak rate" refers to the rate of fluid per unit of time under a given set of conditions, and is properly expressed in units of mass per unit time. Modern leak testing is thus based on the notion that all containment systems leak, the only rational requirement that can be imposed is that such systems leak at a rate no greater than some finite maximum allowable rate, however small that may be as long as it is within the range of sensitivity of a measuring system.

There are two basic types of leaks : one is an essentially localized i.e., a discrete passage through which fluid may flow (crudely, a hole). Such a leak may take the from of a tube, crack, orifice, or the like. A system may also leak through permeation of a somewhat extended barrier; such a leak is called a distributed leak. Gases may flow through solids having no holes large enough to permit more than a small fraction of the gas to flow through any one hole. This process involves diffusion through the solid and may involve various surface phenomena such as absorption, dissociation, migration, and desorption of gas molecules.

A distinction may be drawn between "real" and "virtual" leaks. Real leaks are the type described above; "virtual leak" refers to gradual desorption of gases from surfaces or components within a vacuum system. It is not uncommon for a vacuum system to have real and virtual leaks simultaneously.

It is convenient to categorize leak-testing methods according to whether the method is primarily applicable to the testing of internally pressurized systems or to vacuum systems. There are two basic ways to detect leaks in internally pressurized gas systems: (1) any reduction in the total quantity of gas contained within the system may be detected and (2) the escaping gas may itself be detected. For small leaks in pressurized gas systems, some method of directly sensing the escaping gas is usually necessary, especially when it is essential to locate the leak. Some of the methods used for this purpose are described here. The sound produced by the

escaping gas may be listened to. The pressurized test system may be submerged in a liquid bath and visually observed. A soap solution may be applied on the outer surface of a pressurized system and bubbles formed due to escaping gas be observed. Detectors which are sensitive to specific gases may be used such as mass spectrometers as helium leak detectors and the radiation detectors for detection of leaking radioactive krypton-85 gas. The leak testing of vacuum systems also makes use of several specially adopted versions of specific gas detectors.

Typical applications of leak testing include testing of metals and non-porous materials, enclosures and seals, vacuum leak test of experimental and operating equipment, testing of welds, testing of brazing and adhesive bonds, testing of vacuum chambers and metal gasket seals, reactor fuel element inspection and testing of liquid-metal containers and components.

The application of leak testing techniques is, however, limited because direct access is required to at least one side of the test system and special type of sniffer or probe is required. Smeared metal or containments may plug the leak passage. Radiation and other residual gas hazards are possible.

3.7.7 Radioisotope gauges

While passing through materials radiations are attenuated in accordance with the attenuation law ($I = Io\ e^{-\mu x}$) which says that the intensity of radiation emerging out of the material under test is dependent upon the initial radiation intensity incident on it, the thickness and density of the test material and the energy of the incident radiation. With radiations from a known source the emergent intensity could be related to the thickness and the density of the test material. In practice this is done by having a collimated beam of X, gamma or beta radiations and aligned with this an appropriate radiation detector. The material to be tested is placed in a well defined and fixed geometry between the source of radiation and the detector. The system is first calibrated using specimens of standard thickness and densities and then the intensity emerging from the test material is compared with these values and the corresponding thickness or density determined. The level of fluids in containers can also be measured.

Radioisotope gauges can be applied to metals, non-metals, composites as well as mixed materials usually in the shapes of sheets, plates, strips, tubes, plated parts and reactor fuel elements. They can be used for on-line monitoring of metal and other processing as well as for resin to fibre ratio evaluation in laminar composites. Similarly radiations back scattered from test specimens could also be measured for an indication of fine variations in coating or surface layer thickness and elemental distributions. Neutron radioisotope gauges are used for determination of moisture content in the soil and other moisture measurement applications. The limitations of radioisotope gauges are that access is needed to interpose the test object between the source and the detector. Beam collimation and alignment is critical for accuracy of measurements. Determination of the nature of flaws is ambiguous. Beta rays are limited to very thin sheets and coatings

applications. For the back scatter type gauges a close proximity to the surface is required and special miniaturized probes are required for adequate spatial resolution. In general precautions have to be taken against the radiation hazards.

3.7.8 Analytical methods

The analytical non-destructive methods include chemical spot test, laser probe, X ray fluorescence analysis, X ray diffraction analysis and neutron activation analysis, etc. In the chemical spot test chemical identifications are made by combining the specimen particles with a series of reagents and the colour or phase boundary changes are visually observed and interpreted in comparison with standardized known data. In the laser probe method a laser beam is microfocused on the test object to determine composition and microstructure. Minute quantities of vapourized material which have been removed from the test object are spectroscopically analysed. The X ray fluorescence analysis method utilizes an X ray radiation source to irradiate the surface of the test specimen. The atoms of the test specimen are excited and emit X rays which are characteristic of the atoms emitting them. Spectrographic measurement of these characteristic X rays therefore helps to identify the elemental composition in comparison with standard specimens. For X ray diffraction a sample of the test specimen is exposed to X rays and the scattered radiation intensity is measured which varies with the diffraction angles characteristic of the test specimen. Neutron activation analysis is based on the fact that neutron bombardment of a test object induces radioactivity in it. Every element present becomes radioactive to some degree. Spectrometric analysis of this induced radioactivity then helps in characterization and identification of elemental composition of the test specimen.

The non-destructive chemical analysis methods as briefly described here can be applied to indefinite range of solid and liquid materials specially for metals and their alloys. However, in the chemical spot test it is difficult to establish quantitative values of constituents detected. The analytical accuracy of laser probe method is only of the order of about 5% while the accuracy with activation analysis extends down to ppm level. Both for X ray fluorescence and diffraction the surface of the test specimens have to be cleaned and prepared for high accuracy. These as well as neutron activation analysis present definite radiation hazards.

3.7.9 Miscellaneous methods

In this section it is intended to only make a mention of the methods of non-destructive testing which could not be mentioned in the previous sections for purposes of brevity and to which a reference is considered fit to be made in order to somewhat complete the spectrum of NDT methods. The methods which are to be included here are holographic interferometry (optical and ultrasonic), microhardness measurements, volatile liquids, filtered particle testing, radioactive gas penetrant, positron annihilation, static magnetic field, nuclear magnetic resonance, Barkhausen effect, electrified particle, corona discharge, dielectric, electron emission, acoustic impact, sonic vibration, eddy sonic vibration, contact thermometry, thermoelectric probe, electrothermal, electrolytic probe, ion scatter,

Auger analysis, charged particle activation, Mössbauer analysis, track etch radiography, video radiography, video thermography, photographic extraction, laser filtering, image scan digitization, video enhancement, ultrasonic spectroscopy, sonic signature analysis, etc.

3.8 FUTURE DEVELOPMENTS IN NDT

Future developments in NDT should in principle be seen from two viewpoints, that of the developing countries and the developed countries. For developing countries such as most of the RCA countries of the Asia and Pacific region the future lies in developing the applications of conventional or basic methods of NDT which have been described in Sections 3.1 to 3.6 for various national industries that exist in different countries. In this regard they will be duplicating facilities and efforts which the developed countries undertook when they were at a similar stage of industrialization. In this case the process may, however, be expedited by the presence of multinational companies in most of the developing countries, by the opportunities of education and training that are available to the nationals of present-day developing countries and through the efforts of UNDP and IAEA which are being put in by way of programmes like UNIDO and RCA. With or without these helping programmes the developing countries will need to establish professional NDT societies to organize various works and activities related to NDT. A sound programme for training and certification of NDT personnel will have to be chalked out. This should include as a minimum the issuance of a national standard document on training and certification, creation of a national body to supervise the process at all levels of competence, buying or fabricating a range of NDT test pieces with simulated defects, establishment of one or more institutions which carry out developmental work related to NDT including the repair and maintenance of NDT equipment. Simultaneously efforts will need to be made to keep abreast with the developments taking place in the field of NDT in the developed countries both with respect to equipment and instrumentations as well as the applications.

In the developed and technologically advanced countries the NDT will continue to play a vital role for quality control of industrial products without which it may almost be impossible to survive in the highly aggressive and competitive world market. It may not be totally out of place to say that the relative share of a particular country in the world market will depend more and more on its investment in quality control and quality assurance which in real terms and in most cases may mean an investment in NDT. The NDT equipment will need to be made more reliable and sensitive with a trend to make them as much independent of the operator errors as possible. This definitely points to a greater use of computers and automation. Thus the future will see X ray machines, ultrasonic flaw detectors and eddy current equipment with microprocessors and computers. Data collection and analysis methods will be computerized for ease of reliability, reproducibility and increasing the speed of inspection. We will see the NDT methods of image processing being developed further. The techniques such as computer tomography, laser interferometry and holography and acoustic emission, etc. will be developed further. Increased use will be made of multiple transducers and multiple frequencies with both eddy current and ultrasonic inspection methods. The concept of using simultaneously or otherwise multiple methods of inspection

such as, for example, combining radiography, eddy current testing and ultrasonic testing will be reinforced. An increase may be seen in the use of real-time and on-line or in-service inspection. Radiographic microfilming techniques or computer digitizing techniques may gain popularity to reduce the volume of accumulated hard copy data. To cope with the increased use of composite materials and exotic new metals high sensitivity test methods such as microfocus radiography or high frequency ultrasonic testing will be needed.

There is a growing recognition that the true role for NDT should be in process control rather than in the traditional testing of finished products to meet, in spirit, the requirement of a good quality assurance concept of making the products right the first time. Such a shift toward NDT for process control will simultaneously demand progress in several related fields such as computers and data handling which make it easier to analyse NDT data rapidly and use it in a feedback loop to modify the process. In most cases, process control instrumentation implies a complex and multiple-measurement feedback system that requires a significant investment for using, development, construction and marketing. Due to these reasons it is expected that big companies like Siemens, Philips, Kodak, Dupont, etc. will enter the field of NDT specially for process control and large installations employing automated radiography, tomography, ultrasonics, eddy currents, optical-visual testing and infrared testing will be developed for use specially by industries that have large production output. These larger companies are expected to play greater roles in developing the NDT systems on the one hand and controlling the NDT world market on the other.

3.9 COMPARISON AND SELECTION OF NDT METHODS

Basic principles and procedures of testing along with the typical applications and limitations for various NDT methods have already been described under their respective headings. A summary of all these features is comprehensively presented in Table 3.3 while Table 3.4 gives a rough guidance on the selection of a suitable technique of NDT for a particular inspection problem.

TABLE 3.3 : COMPARISON OF NON-DESTRUCTIVE TESTING (NDT) METHODS

Method	Applications	Advantages	Limitations
Visual Testing (VT)	Surface discontinuities: cracks, porosity, slag, misalignment, warpage, incorrect size or number.	Inexpensive, fast, simple, apply during processing. Can eliminate need for other methods.	Surface only, variable and poor resolution, eye fatigue, distractions. Needs good illumination.
Penetrant Testing (PT)	Surface discontinuities: cracks, porosity, seams, laps, leaks.	Inexpensive, easy to apply, more sensitive than visual, materials, rapid, portable.	Surface only, not useful on hot, dirty, painted, or very rough surface. Requires some technique.
Magnetic Particle Testing (MT)	Surface and near surface discontinuities: cracks, voids, porosity, inclusions, seams, laps.	Low cost, fast, more sensitive to tight cracks than PT, can do near surface, portable.	Material must be ferromagnetic, surface must be clean and good contact made, part may need demagnetization, alignment of field is important. Requires operator technique.

TABLE 3.3. (cont.)

Eddy Current Testing (ET)	Surface and near surface discontinuities: cracks, seams, composition, thickness, eccentricity, surface condition.	Extremely rapid, can be automated, very sensitive, surface contact not necessary, permanent record.	Shallow penetration, conductive materials only, may require special equipment, sensitive to geometry, difficult interpretation sometimes.
Ultrasonic Testing (UT)	Surface and deep subsurface and volumetric discontinuities: cracks, laminations, porosity, lack of fusion, inclusions, thickness.	Rapid if automated but manual is slow, applicable to very thick specimens, can give location and size of defects, good sensitivity, inspect from one side, portable.	Couplant required, thin complex shapes are difficult, orientation of defect important, very operator dependant.
Acoustic Emission (AE)	Surface and subsurface discontinuities: crack initiation and growth, leaks, boiling and cavitation, phase changes.	Remote and continuous surveillance, location, severity, permanent record. Tests an entire vessel or system.	Contact with system, may need many contact points, complex interpretation, system must be stressed, usually expensive, some systems are too complex.
Dynamic Testing / Vibration analysis	System abnormalities misalignment, lack of bonding, missing or worn components, loose parts.	Useful in predictive or preventive maintenance, identify problem areas or parts, indicate severity, in-service test, portable.	Special equipment, experience required, some systems are too complex.
Radiographic Testing (RT)	Subsurface discontinuities: cracks, voids, inclusions, lack of fusion, incomplete penetration, corrosion, missing components	Easily understood, permanent record, usually moderate cost, can be portable, applicable to wide range of materials.	Cannot detect laminations, radiation hazard and regulations, access to both sides, can be high cost, requires trained operators.
Leak Testing	Leaks in systems or subassemblies.	Very sensitive to holes or separations not detected by other methods. Can be rapid and inexpensive.	Costs vary widely with method. Open systems cannot be tested. Type or cause of defect not identified. Can require special materials and equipment.
Thermal Testing	Void or lack of bond or continuity, thin or thick sections, loss of insulation, heat sources.	Detect and locate hot or cold spots and heat generating defects. Permanent record that may be quantitative. Remote sensing, portable.	Poor resolution, often slow, specialized equipment can be expensive and require highly trained personnel. Need reference standards.
Composition & Analysis	Alloy identification, plating identity and thickness.	Rapid, in place, usually not too difficult to do.	Can require considerable technique and experience or very expensive equipment. Very similar alloys difficult to identify.
Miscellaneous	Special.	Can solve special problems.	Equipment not readily available, results not readily acceptable or interpretable.

TABLE 3.4: METHOD SELECTION GUIDE FOR NON-DESTRUCTIVE TESTING OF MATERIALS

Material	Inspection Task	1. Visual Inspection	2. Thermography	3. Optical Metrology and Holography	4. Liquid Penetrant Inspection	5. Magnetic Particle Inspection	6. Eddy Current Testing	7. Magnetic Flux Leakage Methods	8. Potential Drop Crack Sizing	9. Radiography	10. Television Fluoroscopy: Real Time Radiography	11. Neutron Radiography	12. Ultrasonic Flaw Detection	13. Ultrasonic Thickness Gauging	14. Acoustic Methods	15. Acoustic Emission Methods	16. Leak Testing	17. Plant Condition Monitoring	18. Stress Measurement	19. Coating Thickness Measurement	20. Other Methods
Metals	Surface opening cracks	☆☆			☆☆	☆☆	☆☆	☆☆	☆☆	☆☆	☆				☆		☆	☆☆				
	Surface corrosion pits etc	☆☆		☆☆	☆☆			☆☆		☆☆	☆☆	☆		☆								
	Severe corrosion thinning	☆☆	☆	☆		☆☆		☆☆		☆☆	☆☆	☆		☆☆								
	Internal cracks						☆			☆☆	☆	☆	☆☆		☆	☆		☆☆				
	Porosity									☆☆	☆☆		☆☆				☆					
	Lack-of-fusion defects									☆	☆		☆☆									
	Internal voids inclusions						☆			☆☆	☆☆	☆☆	☆		☆							
	Defect sizing	☆		☆		☆			☆☆	☆	☆		☆☆									
	Thickness measurement		☆	☆☆			☆	☆		☆☆			☆☆	☆☆								
	Microstructure variation	☆					☆☆						☆		☆				☆			☆
	Stress/strain measurement			☆						☆			☆						☆☆			
Coated Metals	Coating thickness measurement			☆			☆☆			☆☆		☆	☆	☆							☆☆	☆☆
	Coating delamination	☆		☆			☆						☆☆		☆							
	coating 'pin holes'	☆			☆☆														☆			
Composite Materials	Delaminations and deisbonds	☆	☆	☆			☆						☆☆	☆☆	☆☆	☆						
	Fibre/matrix ration evaluation						☆								☆	☆						
	Incomplete cure of resin												☆		☆	☆						
	Internal porosity									☆	☆											
Concrete	Concrete thickness measurement									☆☆			☆	☆								
	Reinforcing-bar corrosion									☆	☆					☆						
Ceramics	Surface cracks	☆			☆☆					☆	☆		☆		☆	☆						☆
	Internal cracks porosity									☆☆	☆		☆☆		☆	☆	☆					☆
Any	Assembly verification	☆☆		☆						☆☆	☆	☆☆			☆							
	Sorting						☆☆	☆☆							☆☆							☆☆

LEGEND

☆☆ GOOD PROSPECTS

☆ FEW PROSPECTS

4. THE ECONOMIC ASPECTS OF NDT

The decision by the management of an industrial organization about whether to use NDT or not finally boils down to economics. Therefore management should get fully convinced of the economic viability of an investment in NDT. Before we study this problem of costs versus benefits of NDT it seems appropriate to define what we mean by the economics of NDT. Economics of NDT involves an overall impact of NDT on the society taking into account all factors rather than the factor of money alone which is more strictly dealt with under the heading of accountancy. In making these overall considerations there has to be a certain margin of error, guess work, estimation or probability instead of plain addition and subtraction of numbers. Economics has to deal with "values" and services which it is necessary to relate to the universal yardstick of money. Non-destructive testing is essentially a service and is not a direct producer of goods. Also, it is generally easier to determine the ratio of output/input of a factory or organization producing goods than it is to determine the contribution made by individual components within that organization, although they may be rendering a necessary service to the production department. It is in the presence of these factors that the economics of NDT should be viewed. Secondly the need and importance of NDT specially for ensuring safety of plant operations, reducing down time during maintenance, quality control for repairs, in-service inspections and plant life extension should always be considered while assessing the economics of NDT.

4.1 DIRECT COSTS

The true costs of non-destructive testing include such obvious components as inspection equipment, consumable materials, and employee time as well as components which may not be so obvious for example, down time for inspection, and the cost of doing the inspection wrong.

4.1.1 Capital equipment costs

There are two broad categories of NDT equipment. One which is used for general purpose applications and other which is specially designed for specialized or more exotic applications. The equipment in the first category is relatively inexpensive when compared to the cost of the plant or equipment to be inspected. Modern test equipment is designed for use in rugged conditions, is relatively easy to maintain and does not become quickly obsolete. In terms of relative capital costs, one might consider portable computer-based ultrasonic systems to be most expensive, followed by radiography equipment (along with film handing accessories), followed by simple eddy current equipment, magnetic particle inspection equipment and liquid penetrant inspection equipment. Less than one hundred dollars would cover the costs of a set of aerosol penetrant products. An intermediate level portable system using fluorescent penetrants either in bulk or aerosol and a black light would cost in the order of US dollars 500. Custom built and viewing booths could add another $500 to this estimate. The only other items needed for a successful penetrant inspection may be gloves and viewing lenses which have a minor cost. Included in a good penetrant inspection kit should also be sensitivity comparator blocks with simulated cracks.

Magnetic particle testing equipment can vary greatly from a very simple one to the automated and more complex. The simple equipment comprising a portable magnetic yoke can be purchased for about $500. Fluorescent magnetic particle inspection gear with a yoke and black light can be purchased for less than $1000. The permanent, complex and automated installations can cost tens of thousands of dollars. Capital costs for eddy current testing equipment will start at less than $1000 for phase discrimination equipment and tens of thousands of dollars for on-line special purpose equipment. The most basic ultrasonic portable thickness gauge can be purchased for under $1000. A more useful portable flaw detector would be in the order of $10 000 for the unit plus some transducers($200–400 each). Higher levels of sophistication, computerization and specialization can quickly surpass the $100 000 level. Radiographic inspection has a much higher entry level. As a minimum, one would need isotope camera, portable (or fixed) darkroom, and safety equipment including survey meters and emergency handling devices. The minimum investment for such a capability would be $25 000. Portable X ray machines start at $10 000. The cost of building a properly protected permanent exposure facility would add to the capital cost as well. An automatic processor for film development would add another $5000 to 10000 to initial cost. A medium level X rays/gamma rays fixed facility would then cost in the order of $50 000. At the upper end, as always depending on the application, the complexity and the level of automation, and the type of equipment used it is easy to surpass $100 000. With betatrons and linear accelerators used for high energy radiography of thick and dense materials the cost of the inspection facility can even exceed a million dollar level. However, the specialized applications for which such machines are used still fully justify such a large investment. Similarly the specialized automated systems based on ultrasonic and eddy current testing used for in-service and maintenance inspection of radioactive reactor pressure vessels can also cost in the range of millions of dollars.

4.1.2 Consumables costs

Because the film used in radiographic testing uses a silver based emulsion, it is perhaps the single most expensive consumable item in NDT. Each inspection requires at least one sheet of film at a cost of $1–5 per sheet. The chemicals used in developing this film can also be relatively expensive and consumption is generally tied to the number of films processed and thus to the number of inspections. The next most expensive consumable would be the penetrant materials used in liquid penetrant inspection. In terms of consumables cost, the aerosol can would be the most expensive. Savings can be achieved by buying materials in bulk, but the final cost is still generally tied to the number of inspections. Nevertheless, the cost of penetrant consumables, on an average per item basis would be less than 5% of the per item cost of radiographic supplies.

In magnetic particle testing, there is an expense associated with the magnetic particle media which are negligible on a per item basis.

In ultrasonic inspection, consumable materials include liquids and greases used as couplant between the transducer and the test surface. Again this is negligible on a prorated basis. Some organizations treat transducers as a consumable, on the basis that their life is somewhat limited by the degree of use, but on a per inspection basis this cost is insignificant. Similarly eddy current testing has no consumables cost

except perhaps related to wear and tear of the transducers. Funds must be budgeted for equipment maintenance however, and, perhaps the most important use-related cost is for ultrasonic testing equipment. This cost might average 5–10% of the capital cost per year.

4.1.3 Manpower costs

The human cost of the five most common NDT methods can be divided into two categories; the first, preparation time to develop a competent operator; the second, actual time on the inspection task. Recent trends in non-destructive testing have been in two basic directions, on the one hand, to eliminate the human factor to the greatest extent possible through automation and computerization and, on the other hand to make the human component as reliable as possible. The result has been increased dependence everywhere on formalized qualification and certification programmes for operators which specify minimum levels of formal training and experience. The highly developed personal skills required in NDT mean that a good portion of the budget must go for operator training and qualification. Such costs include a threshold cost related to initial training and qualification, perhaps $2000–3000 per method, and a maintenance cost related to continuing education and certification renewals. Obviously such costs on a prorated basis decrease rapidly the more work the individual has.

All NDT methods are operator intensive. The use of highly skilled personnel means that operator time (and thus test execution time) is the most significant cost variable associated with NDT. Radiographic testing operations are particularly costly in this regard. Safety regulations usually dictate the use of a two man crew. Each test requires set-up time, the actual duration of the exposure, the time it takes to develop the film, and then to interpret it. A single weld radiograph could typically need 2 elapsed hours or 4 man-hours. Obviously, economics are possible through work organizations and streamlined setup procedures, but this 2 hours could be considered a minimum requirement. Penetrant inspection requires procedural steps of specific minimum duration during execution as well. A simple test would require a minimum of one half hour for one person. The handling of samples required for magnetic particle inspection establishes minimum execution times, however, these are usually less than those for the comparable penetrant test because pre-inspection cleaning is less critical and there is no need for a dwell time or a developing phase.

For eddy current and ultrasonic inspection, the major time requirement is for calibration, before the test, as the test itself would take only a few minutes. As far magnetic particle inspection, a typical simple crack detection test would take 10 to 15 minutes minimum. In summary it is clear that, subjectively speaking, radiography is the most expensive NDT method when all factors are considered. Magnetic particle inspection would seem to be the least.

4.1.4 OTHER COSTS

Non-destructive testing should not be considered in isolation while calculating its cost. Consideration must be given to the cost and time required for access, scaffolding, surface preparation, transport and insurance, etc. In many cases,

specially for radiography, work in the area may have to be stopped due to radiation hazards thus resulting in a loss of production time.

Another aspect which has a bearing on the cost is the decision as to how much and how frequently is the NDT to be carried out. In assessing the extent of any non-destructive test, many factors may have to be taken into account. All non-destructive testing methods are complementary and generally it is desirable to have the widest possible range of equipment, skills and experience. It is of little value having the best ultrasonic operator in the world if the job requires radiography and vice-versa. There is thus an optimum economic number of people and range of equipment. Similarly the stage at which NDT is applied in a production process has a significant influence on the cost. For example if defects could be located at the ingot stage and the item rejected because of these defects then all the subsequent costs of forging and machining would be saved as compared to the fact that the finished product was inspected and rejected at the final stage. In case of welding where repairs of critical components are quite expensive, it would be advisable that the rejectable defects are discovered and rectified in the first pass before being covered with the succeeding weld beads. For this reason a combined system of concurrent welding and NDT is more beneficial than two separate set ups i.e. one for welding and one for NDT at the final stage of welding.

There is also the cost of an incorrect interpretation which must be considered as part of the human component. Machinery removed from service because of a suspected but ultimately nonexistent defect will result in an inspection-related cost, a cost which should be considered when weighing the need for training and qualification.

4.2 DIRECT BENEFITS

The cost of NDT is usually only a small fraction of the benefit derived, although it is not always easy to quantify the benefit. In some circumstances, however, quantification is simple for example where NDT eliminates the need for disassembly and visual inspection, or where NDT permits 100% inspection of a production run versus say, 10% destructive sampling, or where the confidence generated by NDT allows a plant to keep running instead of shutting down for immediate repairs.

One innovative approach to budgeting for inspection is practised in a large industrial operation, where NDT has been used for many years in support of plant maintenance, with an effectiveness that has established absolute credibility. When the maintenance department runs into a problem that needs a NDT solution, the first question is how much the problem is costing the operation. Once this figure is established, a budget for solution of the problem is established with an upper limit of fixed proportion to the cost say 50–70%. While it is obviously requisite that the NDT group is trusted not to waste time and money to pursue non-feasible solutions, this approach does establish necessary parameters before the project starts, including a minimum cost benefit ratio and maximum freedom for the NDT group to purchase special equipment.

4.2.1 NDT vs dismantling

Non-destructive test methods can save substantial time by eliminating the need for dismantling or disassembly. In aircraft maintenance, for example, examination of internal structural components (such as wing ribs) now carried out by radiographic inspection, could only otherwise be accomplished by removing (and replacing) the outer skin.

Aircraft are normally maintained by scheduling periods in which servicing and repair are accomplished. Unscheduled maintenance, due to structural failure can cause considerable delay for the necessary repairs. These unscheduled out-of-service periods can cost the airlines considerable amount of money. It is estimated that the loss of revenue can range from $25 000 to $50 000 per day. If a major repair is necessary, the downtime can be from two weeks to one month. The downtime is affected by the complexity of the repair and the availability of repair kits or spare parts, which can also be expensive. Initial price of a typical aircraft could be in the range of $30 to $40 million, hence the strong desire and need to apply additional supplementary inspections until such time as extensive fatigue cracking is detected and the aircraft is retired from service.

In another case study on lamellar tearing, NDT provided a means of leaving existing structures in place. When large sections are welded the heat of the welding creates expansion in the metal. When the weld cools, the metal contracts. If the joint is highly constrained i.e. if it offers little leeway for expansion and contraction, the steel may tear. While this type of tearing was first noticed in the US in the mid - 1960s, the first open and serious discussion began in 1972. While research continued over the next few or more years, the American Institute of Steel Construction alerted its members to the potential problem. In the public discussion that followed it was reported that lameller cracking had been observed on large skyscrapers in several cities and that expensive corrective action had been required.

Of specific interest in NDT, however, was the prominent role played by ultrasonic testing in assessing the problem and in restoring confidence. The owner of the 50-storey Trans-American Tower in San Francisco insisted that, until 80–90% of the load is on, all connections continue to be checked ultrasonically. The 110-story Sears Tower, containing more than 100 000 pounds of welds in its connections, required 775 000 inspections and tests, most of which were by ultrasonics.

While solution of the problem lay in a combination of design, welding procedure and base metal, it is clear that had an ultrasonic testing procedure not been available, a good number of these sky scrapers would have been dismantled because of lack of confidence in the integrity of the weld. Tears can occur in steel in the vicinity of welded connections which are easily detected by ultrasonic testing.

4.2.2 NDT and destructive tests

In many cases, the appropriate use of an NDT method can eliminate the need for destructive testing. A detailed comparison of non-destructive and destructive testing has been drawn in Section 2.1.3 which shows the distinct benefits of using NDT as compared to destructive testing. In summary these benefits are the

possibility of 100% inspection of objects actually going into service, the possibility of carrying out numerous tests on the same object simultaneously or in a sequence, capability of in-service inspection without having to stop the process or dismantle the plant and the speed of inspection. These benefits no doubt will need to be considered when looking at the overall economics of NDT.

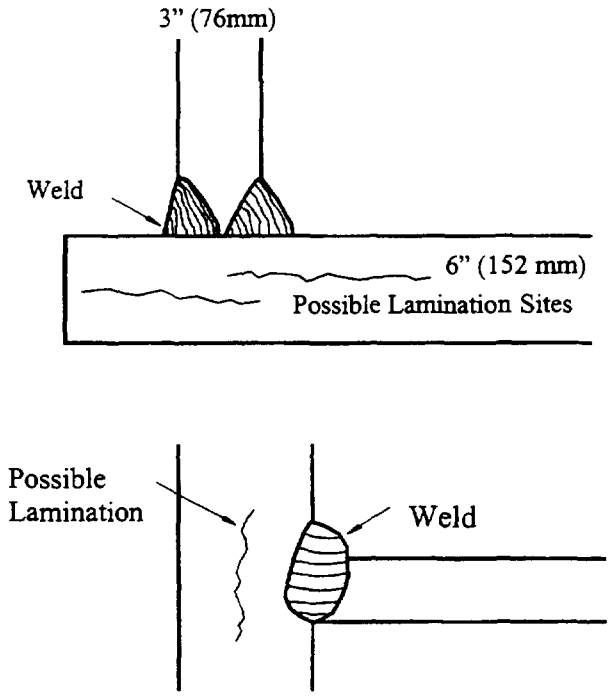


Figure 4.1 : Diagram showing possible lamination sites in weldments.

4.2.3 NDT vs shutdown and replacement

NDT is used in preventive maintenance to avoid downtime due to component failure. Most industrial operations provide for scheduled maintenance shutdown; component failure (or impending failure) between shutdowns can be costly. NDT carried out during a regular shutdown to locate all potential problems can permit rectification action during the shutdown and then guarantee trouble-free operation.

A related application is one which used NDT to identify a problem at an early stage (such as a crack on a shaft or wall-thinning in a tank). The plant may go back into operation, perhaps with regular on-stream monitoring, while a replacement is being machined, or scheduled for the next regular shutdown. NDT also permits, in many cases, a more thorough inspection. A fleet of military aircraft, for example might have its overhaul frequency reduced (number of flying hours between overhaul increased) because NDT is more thorough than even regularly scheduled visual inspection.

4.3 INDIRECT FACTORS

In addition to the identified areas where the benefits of NDT can be quantified, and the substantial benefits from disaster prevention, there are some indirect benefits or costs that must be taken into consideration.

4.3.1 Cost of not doing NDT

The cost of not doing NDT in many situations would be colossal and even unbearable. Let us imagine for a while the consequences of failure occurring in an aircraft, a ship , a railway train, a chemical plant such as a refinery or a plant producing insecticides, a nuclear plant, a pipeline carrying oil or gas or other expensive fluids and many other similar situations in industry. The consequences in all these cases in terms of loss of costly machinery and equipment, lost production and even loss of human life would be colossal as has already been mentioned. Failures in most such cases are a result of cracks and other defects which result in untimely fracture of critical components such as boilers and boiler tubes, heat exchangers, pressure vessels, valves, piping and piping systems, bolts and fittings, wire ropes, pumps, bearings, springs, propellers and anchors, fans and shafts, gears, welds, carriage supports, etc. Most of these disasters can be prevented by timely use of NDT and therefore should be considered on the benefits side when calculating the cost-benefits ratio of NDT. Further, as industry becomes increasingly automated and the strength of the chain becomes even more dependent on its weakest link, where failure is not merely the failure of one piece of equipment, but the stoppage of a line where time is measured in thousands of dollars per minute, per hour or per day; so, providing the "expensive" non-destructive testing services will be true economy.

4.3.2 Cost of not doing NDT correctly

The Alaska Pipeline case is an example of NDT being specified but not being completely applied correctly. One of the large construction projects of the 1970s was the 1300 km long Alaska pipeline. It was being installed under pressures of season and economics. Welders were working under difficult field conditions, however, there were four levels of quality control to ensure that no defective welds were installed. The twelve metre lengths of pipe were welded (double joint) into lengths of twenty four metres using automated equipment prior to shipment to the field. The shop welds, as well as the field welds, were subjected to 100% radiographic inspection (in addition to visual inspection). Non crack like defects could be removed by grinding and repaired by rewelding. Crack indications, however, called for removal and rewelding (at $2000 per weld). Second repairs were not allowed. Despite this concern for quality and thorough knowledge the project was in the public eye, a field radiographer reported that he had been fired for refusing to falsify radiographs. By the time the investigation, as a result of his allegations was completed, 3955 welds (of a total of 60 000 on the line) or weld radiographs were cited as being problematic. Among others 28 contained cracks, 110 X rays were duplicates of others and 360 records were missing. Ultimately the builder supported, through extensive testing and research, leaving some 1100 questionable welds buried using a fracture mechanics analysis approach. The final cost of reinspection and audit was over $5 000 000. However the direct cost to repair every suspicious weld would have been $ 8 million, plus the cost of the delay in startup due to the repairs which was estimated to be $ 50 000 000.

4.3.3 Cost of fraud

The foregoing example of Alaska pipeline illustrates the potential cost of fraud. In fact it can extend even further when through a fraud and manipulation of NDT results, defects are deliberately ignored and allowed to remain unrectified in critical components which go into service. Now in most cases where extensive NDT is performed on components it is assumed that such components will have a definite level of reliability and serviceability and therefore their planned maintenance schedule is prepared accordingly. But since fraudulently components with defects have been placed in service they would naturally cause premature failure resulting in most cases in colossal losses. In fact falsification of NDT results, possibly to save a relatively small amount of money or effort can destroy public confidence in high technology and high risk industries such as aerospace or nuclear industries. It is primarily for this season that along with the reliability and reproducibility of NDT results, the operator integrity is greatly emphasized because it is mostly with the connivance of the operator that most frauds and falsifications of NDT results are implemented.

4.3.4 NDT and life cycle costs

A ground rule for programme management in making decisions related to NDT is also to consider the overall life cycle costs. Lower life cycle costs may be achieved by doing more NDT at the time of fabrication, say of an aircraft, thereby improving productivity and reliability and reducing down time of the operating system. Life cycle costs are determined by design engineering decisions where the ease of inspection is designed into the components, fabrication inspection requirements, quality assurance functions, in-service and overhaul inspection and life extension programmes. A major cost associated with NDT can result from failure to develop a co-ordinated management plan integrating all these factors with NDT. But if careful considerations are made at the appropriate stage, the cost of NDT is generally insignificant when measured against the initial cost or the life cycle cost of a system.

Separating NDT costs incurred solely in the manufacture of a machine such as an aircraft is difficult. The NDT function is generally placed in a quality and inspection department and the tendency is to merge its costs with all costs associated with quality engineering, product inspection, vendor quality control, quality assurance, and product quality control. All are usually covered under one cost code representing the total quality function. To place NDT costs in perspective with other elements of the quality function, it is found that actual costs of NDT some what approach about 1.5% of the selling cost of the item. Thus , in fact the NDT's contribution at the production stage can even be enhanced further to obtain higher reliability, greater serviceability and lower life cycle costs.

4.3.5 Costs related to accept/reject criteria

The most critical (and often the most unavailable) data for determining an appropriate NDT method involve the acceptance/rejection limits for the

frequency/severity of flaws. The limits determine whether the method would be feasible and how expensive the NDT effort would be. Generally the cost increases exponentially with a decrease in the size of flaws which need to be detected or a decrease in the tolerances. Both these factors require high sensitivity and consequently more expensive NDT equipment as well as more experienced manpower which is relatively more expensive. One of the most important obligations of the designer, when NDT is required, is to establish accept/reject criteria for the inspection. To arrive at this decision, the designer needs input from stress, material and NDT engineers. With this input, a designer can easily establish these criteria and make decisions that result in a viable NDT programme.

4.3.6 Miscellaneous factors related to NDT costs

Inflation and other factors cause business costs to increase steadily, therefore the design, material, NDT and quality engineers must understand the criticality of first-time quality as it relates to life cycle costs.

The NDT methods performed during in-service maintenance may be considerably different from those during manufacture, and these differences may cause problems. The design may not reflect the need or requirement for maintenance inspection in which service-induced flaws such as cracks or corrosion are the major concern. Such defects may occur at or below the surface or at a joint or fastener and may not be accessible for visual inspection. Location, type of flaw, intervening structure, and accessibility may not permit the use of the optimum inspection method. Thus, access ports must often be provided to facilitate the use of the appropriate NDT methods. In-service inspections are accomplished at many different locations under many different environmental and testing conditions. Service maintenance is specified in the inspection manuals prepared by the prime contractor. Inadequate manuals for service inspection represent another cost factor, but one that is reflected in operating costs rather than in the cost of NDT involved in manufacturing. Adequate manuals can be prepared by a co-ordinated effort between structural mechanics (stress) and NDT engineers whose technical expertise is incorporated into the in-service NDT manual and overhaul or maintenance manuals. Work on these manuals usually doesn't start until 90 per cent of the engineering drawings have been released. The manuals are generally required with delivery of the aircraft, although their use will not be required for some time.

Retirement for cause concept (RFC) is a life cycle management procedure and is based on economic evaluation whereby components are inspected and, if unflawed, returned to service. This is done by a combination of fracture mechanics methodology and quantitative NDT. Earlier an arbitrary retirement of the components from service was effected based on calculations of low-cycle fatigue life. Under this arbitrary retirement concept, components are retired at the accumulated time (or cycles) when the first fatigue crack in 1000 identical components is expected to occur. Hence, 99.9 per cent of these components are retired prematurely when the predetermined life limit is reached, as determined by low cycle fatigue estimates, and replaced with new ones. This conservative procedure prevents catastrophic failure but is extremely costly.

NDT usually is a part of a bigger organization and draws support from the entire organization's components such as administration, accounts, procurement, the office staff, the costs of buildings, electricity, gas and telephones. Then there is a definite depreciation of the NDT equipment during use. All these factors also add to an NDT inspection or service.

5. NDT AND QUALITY ASSURANCE

5.1 THE NEED FOR QUALITY ASSURANCE

In any manufacturing, fabrication or production process, the quality of the structure or component produced (or service provided) is a key factor in the long term economic and engineering success of that process. Increasing awareness of the importance of quality in every area of technology has resulted from sensitivity to growing pressure of international competition, more discriminating demands from the marketplace and stricter consumer protection and product liability legislation. Part of this awareness is that consistent quality requires much more than product testing. The need to identify and correct inadequacies well before the final product is ready for shipping or handover has become an economic priority in many industries. Quality Control is required because of changing buyer-producer relationships and major marketplace demands for quality.

The social and economic demands for effective use of materials and production processes to turn out higher technology based products assure the need for quality assurance. Similarly the changing work practices in factories and offices and the need to compete in international markets require total quality control of all products and services.

Because the human factor is of great importance in the quality control operation, special attention must be paid to the personnel in the organization. They need to be educated to the benefits of quality control, they need to feel involved in the quality control process and they must be able to communicate with other personnel on quality control. This allows them to develop a quality control spirit and improved morale necessary to the success of any quality control programme.

Quality circles have been developed in many factories to oversee the quality of products. These involve staff representatives at all levels who meet for short periods of time, e.g. an hour, every week to discuss the quality control of their product and any changes necessary.

Quality control has its roots in the guilds of the Middle Ages where quality was assured by long periods of training. This training instilled in workers pride for the workmanship in their product. Specialization of jobs, as industry grew, meant workers no longer made the entire product. This resulted in a decline in workmanship and alienation of the work force. As products became more complicated it became necessary to inspect them after manufacture. In the 1920s

statistics were applied, initially at Bell Laboratories in the USA, in the development of acceptance sampling as a substitute for 100% inspection. General acceptance of the techniques occurred during World War 2 when the early military standards containing quality control clauses were developed. Subsequently quality control institutes and standards associations were formed. The institutes promoted the use of quality control techniques for production and service, through publications, conferences and training. Standards associations have promoted the development of universal standards which may be adopted as part of the quality control process.

5.2 BASIC DEFINITIONS RELATED TO QUALITY ASSURANCE

5.2.1 Quality

Quality of an industrial product does not mean the best or excellent. On the other hand it is defined as the fitness of the product to do the job required of it by the user. It may also be said to be the ability of the product to meet the design specifications which usually are set keeping in view the purpose and the use to which the product is expected or intended to be put. As stated earlier it would be better to set or define an optimum quality level for a product rather than trying to make it of best possible quality which will unnecessarily make the product more expensive which may not be acceptable to the customer.

In a generalized way, the typical characteristics of industrial products which help in defining and fixing its specifications and quality are chemical composition, metallurgical structure, shape and design, physical properties of strength and toughness, appearance, environmental properties i.e. response to service conditions and presence or otherwise of internal defects. These requirements should be met within the specified tolerances. The cost, of course, is an important component. The ability of an organization to meet quality criteria in production of goods or services will ultimately bear on the profitability and survivability of that organization. If it cannot produce goods to the customer's requirements, it cannot compete except under very abnormal and short-term circumstances. However, if the customer's requirements are impossible to meet, or difficult to meet within the financial constraints imposed, the solution may very well be to redefine the requirement. Insistence on an unnecessarily high performance requirement may be completely impractical. In every industry, in every corner of the world, striving for quality has become a popular activity, applied with more or less success depending on the organization and its level of commitment. It should be recognized that quality is not an accident, rather, it should be planned. Quality cannot be inspected into a product after it is made. Instead, the inspection criteria are only to verify that quality criteria are being achieved. The complexity of management of quality within an organization depends on the complexity of the product and the process as well as on the performance criterion. Once a customer's requirement is accepted, quality is the producer's responsibility.

5.2.2 Quality control

Quality control can be defined as the controls applied at each manufacturing stage to consistently produce a quality product or in another way it is said to be the applications of operational techniques and activities which sustain quality of a product or service that will satisfy given needs, also the use of such techniques and activities. The concept of total quality control is defined as a system for defining, controlling and integrating all company activities which enable economic production of goods or services that will give full customer satisfaction. The word "control" represents a management tool with four basic steps, namely, setting quality standards, checking conformance with the standards, acting when the standards are not met and assessing the need for changes in the standards.

In brief the objective of quality control is to provide the customer with the best product at minimum cost. This can be achieved by improvements in product design, consistency in manufacture, reduction in costs and improved employee morale. The factors affecting product quality can be divided into two major groups. First one is the technological which includes machines, materials and processes and second the human which includes operators, foremen and other personnel. The latter is the more important.

5.2.3 Quality assurance

As the name suggests quality assurance is the taking of all those planned and systematic technical and administrative actions necessary to assure that the item is being produced to optimum quality level and it will, with adequate confidence, perform satisfactorily in service.

Quality assurance is aimed at doing things right the first time and involves a continuing evaluation of the adequacy and effectiveness of the overall quality control programme with a view to having corrective measures initiated where necessary. For a specific product or service this involves verification audits and evaluation of quality factors that affect the production or use of the product or service.

Quality assurance is quality control of the quality control system.

5.2.4 Examination and testing

Examination and testing are those quality control functions which are carried out, during the fabrication of an industrial product, by quality persons who are employees of the manufacturer. Testing may also be defined as the physical performance of operations (tests) to determine quantitative measures of certain properties. Most of the non-destructive testing is performed under this heading.

5.2.5 Inspection

Inspections are the quality control functions which are carried out, during the fabrication of an industrial product by an authorized inspector. They include

measuring, examining, testing, gauging or otherwise comparing the findings with applicable requirements. An authorized inspector is a person who is not the employee of the manufacturer of an industrial product but who is properly qualified and has the authority to verify to his satisfaction that all examinations specified in the construction code of the product have been made to the requirements of the referencing section of the construction code.

5.2.6 Procedure

In non-destructive testing, a procedure is an orderly sequence of rules or instructions which describe in detailed terms where, how and in which sequence an NDT method should be applied to a production.

5.2.7 Technique

A technique is a specific way of utilizing a particular non-destructive testing method. Each technique is identified by at least one particular important variable from another technique within the method (Example: RT method-X ray/gamma ray Techniques)

5.2.8 Report

A report of a non-destructive examination or of testing is a document which includes all the necessary information required to be able to:

(i) Take decisions on the acceptance of the defects by the examination.
(ii) Facilitate repairs of unacceptable defects.
(iii) Permit the examination or testing to be repeated.

5.2.9 Records

Records are documents which will give, at any time in the future, the following information about a non-destructive testing examination, (i) the procedure used to carry out the examination, (ii) the data recording and data analysing techniques used, and (iii) the results of the examination.

5.3 RESPONSIBILITY FOR QUALITY

The departments responsible for quality are listed in Figure 5.1. Quality is not the responsibility of any one person or department; it is everyone's job. It includes the assembly line worker, the typist, the purchasing officer and the managing director.

The responsibility for quality begins when marketing department determines the customer quality requirements and continues through to the satisfied customer.

As can be seen from Figure 5.1 the responsibility for quality is delegated to all departments. Each has the authority to make quality decisions. The figure also shows the ideal place for an effective quality control department; it is independent, reporting directly to upper level management.

5.3.1 Inspection and test department

Inspection and test department has the responsibility to appraise the quality of purchased and manufactured items and to report the results. These results can be returned to other departments so that corrective action can be taken when necessary.

In order to perform inspection, accurate equipment is necessary. This means it must be maintained and regularly calibrated.

It is necessary to continually monitor the performance of inspectors. Some defects are more difficult to find and require more patience. Inspectors vary in ability and the defect level affects the number of defects reported. Samples with known defects should be used to evaluate and improve the inspectors' performance. The reliability of inspection can usually be quantified and is most often affected by the operator and not the possible defects in the component presented for inspection. Education (training) is the most effective way of improving reliability.

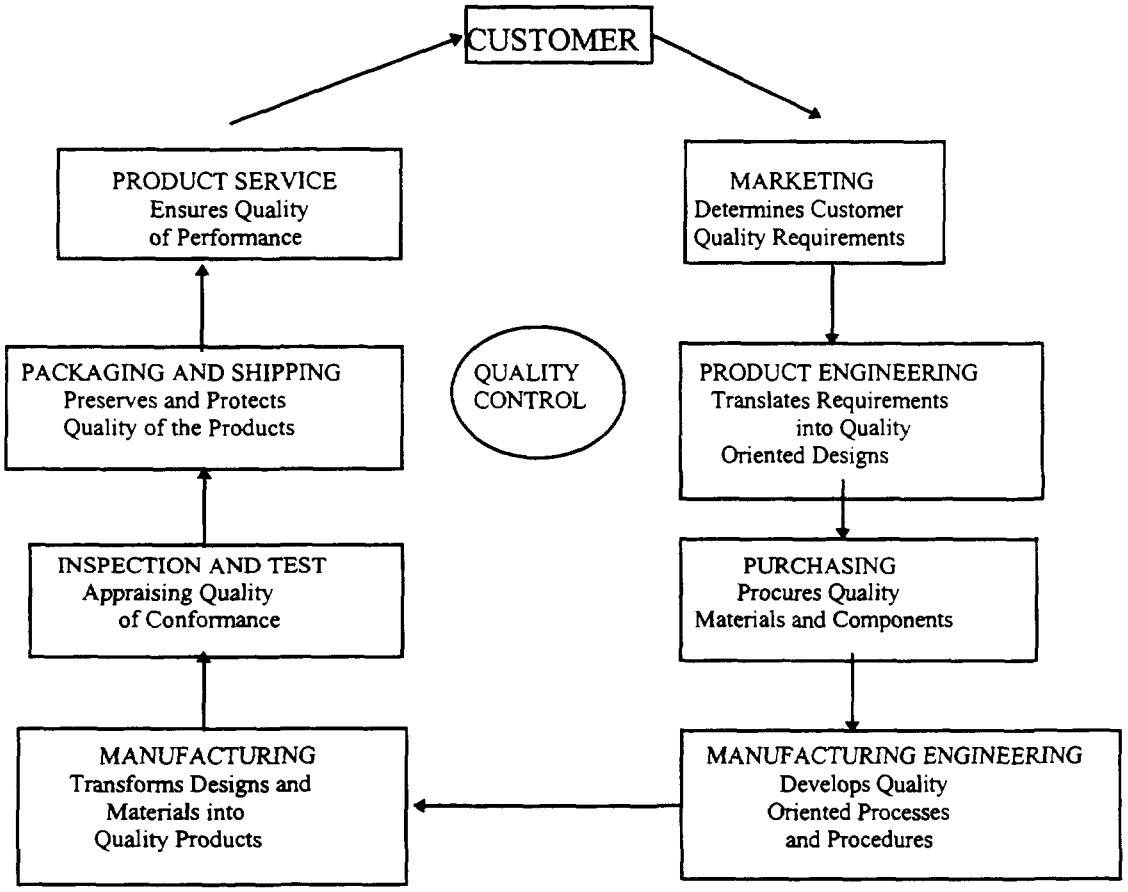


Figure 5.1 : Departments responsible for quality.

5.3.2 Quality control department

The quality control department does not have direct responsibility for quality. It assists or supports the other departments as they carry out their responsibilities.

The relationship between the departments and quality control is similar to a line-staff organizational relationship.

Quality control appraises the current quality, determines quality problem areas and assists in the correction or minimization of these problem areas. The overall objective is the improvement of the product quality in co-operation with the responsible departments.

5.4 METHODS FOR DETERMINING QUALITY

5.4.1 Statistical quality control

The basic concept of statistical quality control (SQC) is that testing of a number of samples can provide sufficient information to allow reasonable conclusions to be drawn about the entire batch. Analysis using statistical concepts establishes the number of samples needed to reliably assess the full quantity. While 100% reliability would require 100% testing, very high reliability, say 90%, can be achieved with relatively small samples, say 10–15%. The sample size depends on a number of factors such as the batch size, nature of the product, the repeatability of the manufacturing process, and the quality required, and can be set in a number of ways. A common method relies on setting an acceptable quality level (AQL). This level is defined as the proportion of defective products that is acceptable to the customer. Standard tables then give the sample sizes to suit the batch size and the AQL, together with limits for the numbers of faulty components found in the sample. If the number of faulty parts found during testing is less than or equal to the lower (acceptance) limits, the batch is accepted, and if the upper (rejection) limit is reached during testing the batch is rejected. When the number of faults reaches the acceptance number part way through the sample, testing is continued until the rejection number is reached, or until all the sample is tested and thus passed.

When a decision to accept or reject a batch of parts is made on the basis of testing a single sample, the technique is known as sampling. This procedure can be refined by the use of more than one test sample. In double sampling the first sample is tested and the number of defective parts checked against the pre-set acceptance and rejection limits, which are more rigorous than for single sampling. Particularly good or bad batches would meet or exceed these limits, and thus be immediately accepted or rejected, but average batches would lie somewhere between the limits. In such cases a second sample is taken and tested, and the total number of defective parts from both samples is compared to a new set of limits. The rapid acceptance of good batches, and rejection of bad ones, with this system reduces the total amount of testing and thus helps reduce costs.

This basic principle can be extended to multiple sampling where a series of samples are taken and tested in turn, and to sequential sampling in which the samples are tested one at a time. After each part has been inspected, the cumulative results obtained from the parts tested so far are examined using an appropriate sampling plan to see if the results justify either accepting or rejecting the batch. If the decision is not conclusive in either way the process is repeated

with another part. This sequential approach is more complex than straightforward batch testing but generally involves the testing of fewer components.

In general, the greater the sample size, the greater the reliability that the sample is a true indicator of the entire batch. The economic decision is to weigh the reliability of the sampling test against the increasing cost of inspection as the sample size approaches 100%. For some applications, the need to have 100% freedom from defect and the costs associated with this higher level of reliability must be carefully considered.

For example, consider a machining process in which a piece of metal is ground down to a thickness of 0.5 in. (12.7 mm). The tolerance or variation allowed in the specification is 0.005 in. (0.127 mm), and thus any pieces in the thickness range of 0.495 to 0.505 in. (12.57 to 12.83 mm) would be acceptable. With an accurate machine the actual production would be more precise, and a series of parts might average out at, say, 0.502 in. (12.75 mm). If the next set of measurements gave a slightly larger mean value of 0.503 in. (12.78 mm) (still well within tolerance) it could be assumed that the machine is starting to move out of tolerance and appropriate adjustments might be made before any out-of-tolerance work is produced.

It is common to use control charts to facilitate the inspection work and to keep the production of parts within the specifications. Generally there are two kinds of these control charts which are more commonly used. These charts will be explained through another example wherein an order has been placed for the production of some 450 000 bolts with the specifications of the bolts having an average tensile strength of 6990 kilograms and a standard deviation of tensile strength which does not exceed 250 kilograms. First of these charts are based on arithmetic average and one such chart is shown in Figure 5.2. The horizontal line drawn at 6990 kilograms represents the goal set for the average. The horizontal lines drawn at points 103 kilograms above and below the desired average for all bolts mark off the safety zone for the averages of 25 bolts in each sample. As long as average of 25 bolts falls in this zone the production is considered to be under control because no evidence has been encountered which conclusively proves that the production is out of control. However, as soon as average such as the point C falls in the lower shaded area, careful check should be begun on the production process. If the production is still satisfactory, the sample average marked C would occur due to chance alone less than 2 times out of 100. Stated in other words, there are less than 2 chances out of 100 that the production is resulting in bolts that really average at least 6990 kilograms in tensile strength. Since the average of the bolts made on the twenty-fifth day is probably less than 6990 kilograms, the percentage of all of the bolts that will fall below 6500 kilograms is much larger than the 2.5 per cent specified in the contract.

If the average of a sample of 25 bolts should fall below the lower edge of the shaded band, the statistician should warn the production superintendent that the bolts are almost certain to be unsatisfactory. There is only 1/2 chance in 100 (or 1 chance in 200) that the average D could have arisen as a result of a random fluctuation. There is only 1 chance in 200 that the production is satisfactory.

The control charts for the average are drawn using the concepts of degrees of freedom, probability and the standard error. The standard error in this case is $\sigma_M = \sigma/(N)^{1/2}$ where σ is the standard deviation having a value 250 in this case and N is the degrees of freedom which in this case is 25 which is our sample size. This gives a value of 50 kilograms for the value of σ_M, the standard error. The t values necessary for the construction of control charts are obtainable from the relevant t charts. The 5% and 1% values of t for 25 degrees of freedom are 2.06 and 2.79. Multiplying these values with the standard error we get respectively the values of 103 kg and 139.50 kg respectively. These values should be added to and subtracted from the average tensile strength for all the bolts.

6990 + 139.50 = 7129.50 kg
6990 + 103.00 = 7093.00 kg
6990 - 103.00 = 6887.00 kg
6990 - 139.50 = 6850.50 kg

These four values locate the borders of the shaded areas shown on the chart in Figure 5.2.

AVERAGE TENSILE STRENGTH
OF A SAMPLE OF 25 BOLTS

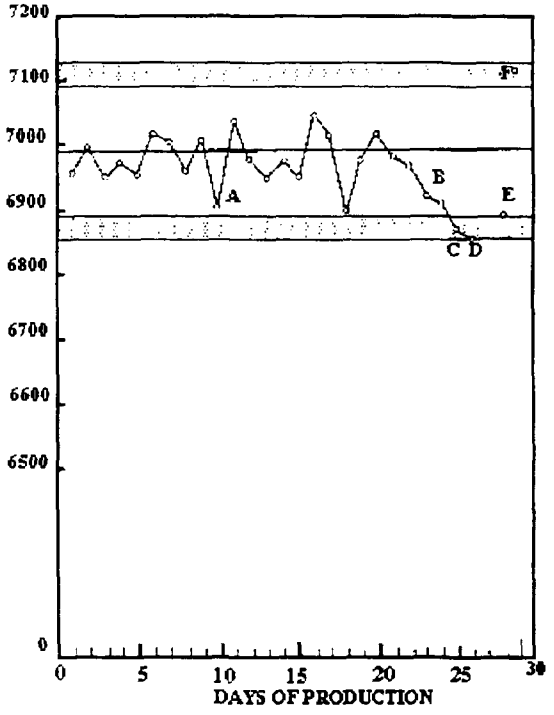


Figure 5.2 : Control chart for the arithmetic average.

It is dangerous to specify only the average. If the bolts are to be used in a large building and only the average is specified, there would be no legal recourse if the bolts varied so much about the average that half the building fell down. The man who manufactured the bolts could calmly say that the rest of the bolts were so

STANDARD DEVIATION
OF TENSILE STRENGTH

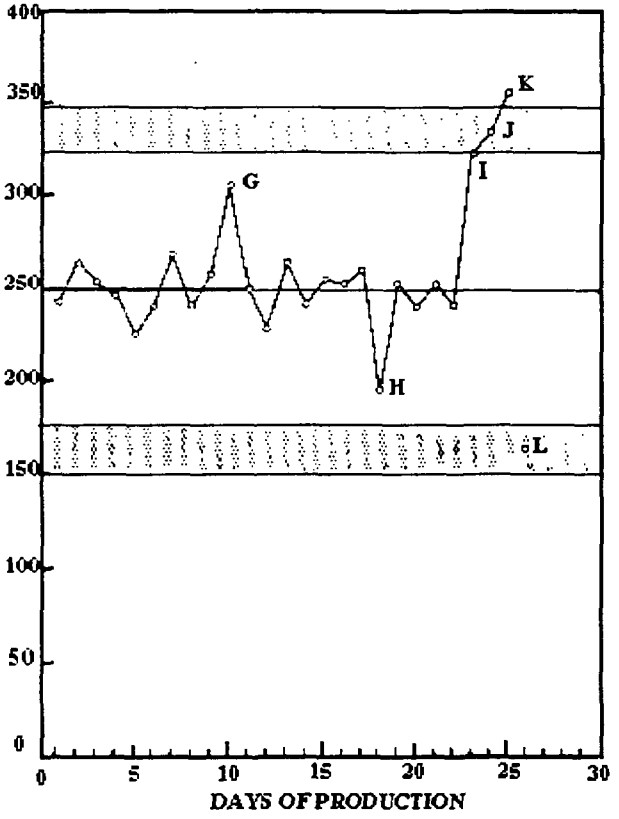


Figure 5.3 : Control chart for the standard deviation.

much stronger than the average that they compensated for the fact that some of the bolts were weak, and that, on the average, the bolts met the specification of the order. A more simple and safe way of specifying the quality of performance of the bolts is to require that not more than a certain percentage of them are to be permitted to have a tensile strength below a specified value. For example, one order reads, "not more than 2.5 per cent of the bolts are to be permitted to have a tensile strength below 6500 kilograms." This restriction could be met by a number of different combinations of the standard deviation and the arithmetic average. The larger the average becomes, the larger becomes the standard deviation that could be permitted without violating the terms of the contract. Stated in other words, the larger the standard deviation becomes, the higher the average must be set in order to have the bolts of a satisfactory quality.

The second type of control charts are those based on standard deviation. In order to construct this chart, we need to compute the standard error σ_σ of the standard deviation which is given by $\sigma/(2N)^{1/2} = 250/7.071 = 35.36$ kilograms. Next we obtain t values for 1% and 5% probability points. These come out to be 2.80 and 2.06 respectively. Multiplying these values with σ_σ as calculated above we get the values of 99.01 and 72.84 kilograms. These values should be added to and subtracted from the standard deviation planned for all the bolts.

Thus : 1 250 + 99.01 = 349.01 kg
250 + 72.84 = 322.84 kg
250 - 72.84 = 177.16 kg
250 - 99.01 = 150.99 kg

Then the control chart as shown in Figure 5.3 is obtained by plotting these four values and the desired standard deviation. As long as a standard deviation computed from a sample of 25 bolts falls in between the two shaded areas, there is no need for serious concern regarding the production. However, as soon as the standard deviation of one sample falls on the edge of the upper shaded area, such as point I, there is serious doubt about the production being under control.

As soon as the standard deviations plotted as points J and K are encountered, it is very improbable that the production is still under control. It is advisable to make a very careful examination of the production methods, employees, and raw materials.

5.4.2 Destructive tests

A destructive test by definition is any test which alters the shape, form, size or structure of the material being tested. The tested part is destroyed in the process and is not available for use for which it had been designed. However, the information obtained is usable for evaluation of other similar parts from the same batch with the help of statistical quality control. Some of the commonly used destructive testing methods are briefly described in the following sections.

5.4.2.1 Hardness testing

Hardness may be defined as the resistance which matter offers to the penetration of a solid body or the resistance of metal to plastic deformation usually by indentation (also see Section 2.2.3).

Brinell hardness testing involves impressing a hardened steel ball onto the surface of the material being tested. The depth of penetration of the ball into the test specimen and the diameter of the circle of the resulting impression are related to the hardness of the test specimen specified in terms of Brinell hardness number (BHN or HB). HB values can either be calculated or determined from specially prepared charts which relate the impression diameter to HB values at different loads. Charts and formulae are also available to calculate tensile strengths from given HB values for different materials. The Brinell test is most often used on large parts specially castings, forgings, structures, etc. Test loads and indenters can be varied, the combination most often used being a 3000 kg load on a 10 mm diameter steel ball.

Rockwell hardness testing utilizes several types of indenters, all of which are much smaller than Brinell indenters. The indenter is forced into the surface of the test specimen. This is done by first applying a minor load to the indenter, followed by application of a major load. The hardness number is determined by the increase in the depth of the impression that results from application of the major load.

There are many overlapping Rockwell hardness scales. These scales vary according to the type of indenter, the minor load, and the major load used. The results are displayed as numerical values followed by HR (hardness Rockwell) plus a letter symbol indicative of the hardness scale used. For example, "20 HRC" indicates a value of 20 on the Rockwell C hardness scale. Many of the various Rockwell hardness scales can be related to one another by use of conversion tables.

The most commonly used specification for Rockwell hardness testing is ASTM E-18. ASTM E-140 covers hardness conversion tables for all metals on all scales as well as tensile strength conversions. Tables are also available for conversion between Brinell and Rockwell hardness numbers.

Microhardness testing involves the principles previously described for Brinell and Rockwell hardness testing. The difference is that in microhardness testing the loads are very low and the indenters are more precise. The loads generally range from 1 g to 1 kg. After the indentation has been made, it is measured using suitable microscope. The microhardness value is defined as the ratio between the force acting on the indenter and the area of the indentation produced by plastic deformation.

There are also some other methods of hardness testing. The Scleroscope hardness test involves dropping of a specific object on the test piece and measuring the height of the rebound. Vickers hardness test is similar to the microhardness test made with the DPH diamond indenter except that large loads are used. Ultrasonic hardness testing is a unique method that leaves virtually no mark. A magnetostrictive diamond-tipped rod is ultrasonically induced to vibrate at its natural resonant frequency. The frequency of vibration changes with the depth of penetration and is read on a meter and compared with readings from standard test blocks. The total depth of penetration is 0.0076 to 0.0127 mm. The test is very rapid but requires very good surface preparation.

5.4.2.2 Universal testing machine

The universal testing machine in its simple form, consists of a device for applying a load to a test specimen and accurately measuring this load continuously as the specimen is stressed. An auxiliary device may be used to measure the specimen's reaction to the applied load. The load-applying device is not unlike a press with two platens. One platen is fixed while the other moves either toward or away from it. A specimen placed between these platens can be pressed together (loaded in compression) or gripped on each end and pulled apart (loaded in tension). This machine is employed for carrying out a number of tests some of which are briefly described below:

The tensile test is made by placing the appropriate specimen in the testing machine between the upper (fixed) and lower (movable) platens (also see Section 2.2.2). The specimens which are specially prepared are retained by special grip. The load is applied at a predetermined rate. The applied load is observed on a weighing scale, dial gauge, or digital readout. An extensometer, a strain gauge, dividers, or some other device is used to observe the response of the specimen to the applied

load. All of these data are recorded and where applicable, compared with established specification. The other measurements we can make during a tensile test are the measurement of specimen extension and reduction in area, latter being applicable specially to the sound specimens. Specimen extension measurements related to applied loads help us in making stress-strain diagram which is the road map for the tensile test. From this map the data such as proportional limit, modulus of elasticity, elastic limit, yield point and tensile strength can be obtained. Reduction in area is a ductility measurement.

Compression tests are commonly performed on materials such as concrete and metal components used under compressive loads such as in structures, cast iron members, certain aircraft members, and others. The principal value is the maximum load per unit area, since the cross section enlarges as the yield point is exceeded. Stress-strain diagrams can be obtained for ductile materials.

Bend tests, as their name implies, measure the ability of a material to react to bending stresses and the quantity of deformation it can withstand. Little is measured or determined other than a go/no-go evaluation, that is, whether or not the specimen will bend or deform by a given amount under either free or restricted conditions without cracking or breaking. This may require measuring the degree of bending, and in some cases gauge marks are located on the outer surface of the bend to determine the ductility resulting from test deformation . The bend test is simple and inexpensive, and is most often used for testing plate, pipe, and welds.

Flattening tests are usually restricted to pipe, more particularly, welded pipe. The test involves placing a short length of pipe between the platens of the tensile machine. If the pipe is welded, the weld is positioned at an angle of 90° to the loading direction. The specimen is subjected to compression loading and the welds or the point of maximum bending, is observed. If cracking occurs, the test is halted and the distance between platens noted.

Shear, as its name implies, is the scissorlike action of fracturing. In service many parts are subjected to shear-type loads. ASTM Specification B-565 gives details of a shear test for aluminium rivets, wire and rod. Most shear tests are individually designed for specific products.

5.4.2.3 Impact testing

Impact testing, as its name implies involves subjecting the specimens to impulsive or suddenly applied loads (also see Section 2.2.7). Impact testing is a particularly useful test procedure for material to be used for parts that will be exposed to sudden loads in service. Impact tests are very temperature-sensitive and therefore test temperatures must be specified and noted. Materials behave quite differently when they are loaded suddenly than when they are loaded more slowly as in tensile testing. Because of this fact, impact testing is considered to be one of the basic mechanical tests (especially and principally for ferrous materials). The property values so determined do not necessarily relate, or convert to, other mechanical test values. The results do predict to some extent the likelihood of fracture initiation under certain specified loading conditions, the likelihood of crack propagation if crack initiation occurs and the effects of concentrated stresses on sudden

applications of load. Most commonly used impact testing methods are Charpy test, Izod test, drop weight test (DWT) and drop weight tear test (DWTT).

Charpy test is a pendulum type single-blow impact test in which the specimen, usually notched, is supported at both ends as a simple beam and broken by a falling pendulum. The energy absorbed, as determined by the subsequent rise of the pendulum, is a measure of impact strength or notch toughness.

The DWT method employs simple beam specimens specially prepared to create a material crack in their tensile surfaces at an early time interval of the test. The test is conducted by subjecting each of a series (generally four to eight) of specimens of a given material to a single impact load at a sequence of selected temperatures to determine the maximum temperature at which a specimen breaks.

In the DWTT the specimen resembles a large Charpy test specimen. The test specimen is usually 3 in (76.2 mm) wide by 12 in (304.8 mm) long supported on a 10 in (254 mm) span. The thickness of the specimen is the full thickness of the material being examined. The specimens are broken by either a falling weight or a pendulum machine. The notch in the specimen is pressed to a depth of 0.200 in (5.08 mm) with a sharp tool steel chisel having an angle of 45 degrees. The resulting notch root radius is approximately 0.001 in (0.0254 mm). One result of the test is the determination of the fracture appearance transition curve.

5.4.2.4 Fatigue testing

Fatigue is a phenomenon whereby materials fracture when exposed to cyclic loading condition where the maximum load cycle is lower than the tensile strength of the material (also see Section 2.4.2.2). If the loading is repeated enough times, fracture may occur even though the loading is not great enough to break the part in one application. Fatigue fracture is often a surprise because there is little warning, and fracture occurs at lower-than-anticipated loads. Fatigue fractures are progressive. They start as small cracks and then grow gradually as the load fluctuates. When loading is particularly high (approaching the tensile strength),very few cycles are required to cause failure. At lower loading levels, up to one million cycles of loading may be required before fracture occurs. Every material has a fatigue strength, or endurance limit, which is inherent to that material, Cyclic loading below the endurance limit will not produce fracture no matter how many cycles of loading are applied. Springs, rotating shafts and aircraft members are but a few of the common parts that are subjected to cyclic loading in their normal usage and are subject to fatigue fracture.

It is believed that fatigue cracking initiates at a point of stress concentration due to highly localized slip-type fracturing (through one or two grains). The second stage is propagation due to the effective lowering of strength caused by the initiated crack, and strain at the crack root. The third stage is rupture, which occurs when the remaining sound metal is not of sufficient cross section to withstand one more application of load and thus a tensile overload failure occurs. Fatigue may result from any type of cyclic or repeated loading, vibration, bending, twisting, pulling,

pushing or any other form of repeated loading that can produce a load in the range of magnitude that will exceed the endurance limit. The three factors which must be present to cause fatigue cracking are: cyclic stress, some component of tensile stress, and plastic strain (may be very highly localized). If sufficient specimens are tested at various load ranges the results can be plotted. Such plots are called S-N curves, S being stress and N being number of cycles. This produces an angular straight line that becomes flat and horizontal when the endurance limit is reached.

5.4.2.5 Metallography

Metallography (writing on metal) is the name given to the science and art of preparing and examining metals under the microscope. A brief summary of the entire procedure is as follows. A small section is removed from a selected area of a metal part. It is mounted, often in plastic, so that it can be held firmly and processed flat, from edge to edge. It is then ground using abrasive papers of decreasing coarseness. After grinding with the finest-grit abrasive paper the polishing phase of the operation begins. Abrasive powders are applied to special surfaces (usually a type of cloth stretched tightly over a flat, metal polishing wheel). After being polished, the specimen is examined in the as- polished or unetched condition. This reveals the cleanness of the material and the presence of any internal defects such as cracks, voids, or entrapped nonmetallics. The polished surface is treated with an etchant such as for example, a 2% solution of nitric acid in alcohol (nital) and is again examined. These examinations are performed using a device such as an inverted-stage metallurgical microscope or a metallograph. The results are recorded, usually by preparing a photograph of the observed microstructure. The pattern seen in a metallograph has been described as the finger prints of the metal. This is probably a good description, because each structure so revealed is unique and distinctive.

5.4.2.6 Chemical analysis

Chemical analysis is a procedure used to determine the elemental make-up of a material and/or the quantity of each component present. It essentially involves isolating the various components of a material and accurately measuring the quantity of each component present. This is accomplished by many different methods, some of which are non-destructive in nature while others are destructive. The non-destructive analytical methods such as X ray fluorescence, X ray diffraction and neutron activation analysis have earlier been described in Section 3.7.8. The destructive type of analytical methods will be briefly discussed here.
Chemical wet chemistry involves chemical dissolution of the metallic sample, isolation, identification and separation of various elements present and quantitative measurement of the amounts of these elements by either gravimetry or titrimetry.

Electrochemical analysis involves separation of the metallic elements in a metal specimen by deposition at controlled voltages. Gravimetric techniques are then employed for quantitative measurement. In a typical method, the sample is dissolved and certain elemental metals are selectively plated out. The plated surface is carefully weighed before and after plating of each element, and this weight is converted to a percentage value for the element.

Atomic absorption spectrometry is the branch of spectroscopy involving the interpretation and application of spectra originating in the absorption of electromagnetic radiation by atoms. A sample solution is sprayed into a flame to atomize the droplets. Light of a specific wavelength related to the element being analysed for is passed through the atomized solution. By a process of absorption, the concentration of neutral atoms of that specific element is measured and recorded electronically. Comparison of the results with those obtained from calibrated solutions determines the concentration of the element present in the solution. This procedure is widely used to determine trace quantities (from parts per million to parts per billion) of about 70 different elements.

Auger ("0-zhay") electron spectroscopy is a highly sophisticated technique used to analyse surface layers ranging in thickness from 0 to 30 Å (0 to about 0.0000025 mm.) Perhaps more often these layers are only 0 to 5 Å thick. This process can be used to analyse for all elements except hydrogen and helium. Surface layers can be removed by sputtering technique, and a composition-depth profile can be developed to show metallurgical surface modifications.

High-temperature combustion analysis is a method whereby elemental separation is produced by high-temperature heating. A quantitative measurement is then made after the element is caused to recombine as a known, easily measurable stable compound. A carefully weighed specimen is placed in a ceramic combustion boat. An accelerator such as tin metal is added, and the boat is heated to 2500°F in a high-frequency or resistance-type furnace. Oxygen is passed over the sample causing it to combust. The carbon and sulphur are released and form oxides, which are isolated and separated from interfering elements. The gases are completely converted to sulphur dioxide, and carbon dioxide, which are then measured by infrared detection or thermal-conductive methods, or are absorbed and measured volumetrically.

Inductively coupled plasma atomic-emission spectroscopy is a method in which plasma-arc ionization is used in conjunction with emission spectroscopy for broad-range analysis in wide concentration ranges. This method is used for simultaneous multielement determinations. The specimen is dissolved and activated in liquid form using the plasma-arc technique to highly ionize the sample at a temperature of 10 000°K. This coupled with emission spectroscopy detection instrumentation, allows analysis of some 70 elements with detection in the parts per million (or greater) range.

Optical-emission spectroscopy is an analysis technique that utilizes spark-arc emission spectroscopy in the visible or near-visible wavelength regions of the electromagnetic spectrum. A properly prepared sample (usually a disk about 25 mm in diameter that has been ground flat) is subjected to a DC arcing current, and the emitted light forms a series of emission lines characteristic of the atoms producing them. The higher the concentration of an atom, the greater the intensity of the emission line. By measurement of these emission lines, the concentration of the elements can be obtained.

Chemical analysis may also be used for such things as corrosion- product analysis, contamination analysis, surface-layer identification, materials characterization, and determination of cause in analysing metal failures.

5.4.2.7 Fracture mechanics testing

The purpose of fracture mechanics testing is to determine the response of a given material to the presence of a crack (also see Sections 2.4.2.4 and 2.4.2.5 and 7.4). We all know that if a part is cracked severely enough, the application of only a small additional load will cause it to break. The real question is how large a load, applied to how big a crack, in a part of a certain configuration and in a material of defined properties, is necessary to produce crack propagation or, for more practical purposes, how large a crack will make the part unreliable for its intended purpose. By use of a combination of mechanics, analysis and materials testing, fracture mechanics allows the determination of the relationship among service stress, material toughness, and critical flaw size. Once the material toughness has been ascertained using one of the described approaches, either critical flaw size or critical service stress can be determined.

Put simply, the fracture mechanics test procedures involve preparation of a test specimen of known geometry and having standard-sized notches, fatigue precracking of the specimens and then loading the specimens to failure. During the process of this procedure data are collected to enable the determination of various variables used in fracture mechanics calculations.

Fracture mechanics is used to assess the significance of flaws detected by non-destructive inspection methods. This can be done before or after the component is placed in service. Fracture mechanics is also being used to ascertain how often it is necessary to perform such inspection of structures or components where cracking may be anticipated. Another area where fracture mechanics has been applied is in the field of material failure analysis. For critical structures fracture mechanics testing quantifies the significance of flaws under service conditions. When used in combination with a programme of periodic, non-destructive inspection, it offers great potential.

5.4.2.8 Miscellaneous destructive tests

Under the heading of miscellaneous destructive tests could be included bearing testing, bend testing, corrosion testing, creep testing, crush test, cupping tests, dilatometry testing, expansion testing, explosion testing, extrusion testing, transverse bend testing, friction testing, grain size fracture tests, high strain testing, machinability testing, macroetch testing, magnetic permeability testing, residual stress measurement, shear testing, spark testing, stiffness testing, stress relaxation testing, torque testing, etc.

5.4.3 Quality control applications of NDT

Quality control of manufactured goods is accomplished by measuring dimensions, properties or other characteristics, comparing the measurements with

predetermined standards and varying the manufacturing process as necessary to control these characteristics. Often direct measurements of characteristics can be accomplished only by destroying the parts. Obviously a product that has been destroyed cannot be sold. The commercial impact of this fact is two fold; costs were incurred to make the product, yet no profit can be made from its sale. However, if the same information can be obtained without destroying the part, even if only as indirect measurement, then the part can be sold for a profit after it has been tested. The commercial incentive to test non-destructively is large when small quantities and large profit margins are involved and is crucial with one of a kind products.

Various methods have been developed for accurately and reliably measuring characteristics of parts without affecting their commercial value. Many of these are indirect methods, but they have gained wide acceptance as tools that can aid both management and production personnel in reducing costs and improving product quality. Also use of non-destructive inspection has become necessary as a means of meeting certain legal and contractual requirements affecting the production and sale of a wide variety of manufactured products.

Factors that contribute to the reliable application of several of the major processes of non-destructive inspection are considered later.

5.4.3.1 Quality of inspection

As with all production processes many quality considerations must be applied to the control of non-destructive inspection processes to ensure that the information being supplied from them is accurate, timely and germane (i.e. relevant). One of the greatest problems of non-destructive inspection has been misapplication which usually meant that the wrong information was supplied. Thus non-destructive inspection sometimes has had only limited usefulness as a production or technical tool. Also only when the capability of a non-destructive process is known in quantitative terms can the inspection results be considered a measure of true product quality.
Successful application of non-destructive methods to the inspection of manufactured goods requires that:

(i) The test system and procedure be suited to both inspection objectives and types of flaws to be detected.

(ii) The operators have sufficient training and experience.

(iii) The standard for acceptance appropriately defines the undesirable characteristics of a non-conforming part.

If any of these pre-requisites is not met, there is a potential for error in meeting quality objectives. For instance, with inappropriate equipment or with a poorly trained operator, gross errors are possible in detecting and characterising flaws. This is of particular concern if it means chronic failures to detect flaws that seriously impair service performance. With inadequate standards, flaws having

little or no bearing on product performance may be deemed serious, or significant flaws may be deemed unimportant.

It is necessary that the types of flaws that can be induced by each manufacturing operation are understood, only then is it practical to define the non-destructive inspection that should be used. For instance, if a forging is inspected for internal forging cracks by radiography it is important to determine the direction of grain flow (and hence the most probable direction of cracking) because any cracks that are not aligned with the radiation beam will usually not be detected. Even when the direction of grain flow is known it may be difficult to orient the radiation beam properly but it is usually easy and effective to inspect the part ultrasonically.

As used in non-destructive testing and quality control, the term 'defect' means a detectable lack of continuity or a detectable imperfection in a physical or dimensional attribute of a part. The fact that a part contains one or more flaws does not necessarily imply that the part is non-conforming to specification or is unfit for use. Similarly the term 'non-conforming' means only that a part is deficient in one or more specialised characteristics. It should not be automatically assumed that a non conforming part is unfit for use. In many instances a non-conforming part is entirely capable of performing its intended function even in its non-conforming condition. In other instances a non-conforming part can be reworked to make it conform to specifications. Of course sometimes a non-conforming part can neither be used nor reworked and must be scrapped.

5.4.3.2 Human factors

Education of all levels of personnel engaged in non-destructive inspection, including formal training, and certification in accordance with government, technical society or industry standards, is probably the greatest single factor affecting the quality of non-destructive inspection. All methods of non-destructive inspection are highly dependent on operators for obtaining and interpreting data. Inadequate education of personnel jeopardizes the reliability of inspection. This applies even to automated inspection which is controlled by the accept-reject criteria programmed into the process. Automatic data analysis techniques must be established, proven and monitored by competent non-destructive inspection personnel. In general, inspection should be performed by personnel who are trained to the national equivalent of ISO 9712 Level 2 in the particular method being used. Supervisory personnel should have skill equivalent to ISO 9712 Level 3.

The effects of human factors on the non-destructive inspection process also must be considered. It has been found through independent statistical studies that different people have widely differing abilities to find all the flaws in a part, even when the same non-destructive process and specific inspection procedure is used. This variability is usually more pronounced with small flaws. There is also a pronounced variation in the effect of factors such as heat, lighting, ventilation, fatigue and attitude on the performance of properly trained and qualified operators. As a result of these studies, confidence curves have been established showing the probability of detection versus defect size for each of the major non-destructive inspection processes. Human factors should always be considered by

the design and quality control engineers when setting maximum allowable defect sizes or while setting accept-reject criteria.

5.4.3.3 Acceptance limits

The setting of accept-reject criteria is important to the quality of non-destructive inspection. Limits that are too strict unnecessarily increase both manufacturing and inspection costs, and often require special manufacturing techniques to meet the strict acceptability limits. Acceptance limits are usually indicated on the design drawing or specification. Often, however, these limits have been selected arbitrarily. It is a function of quality engineering to review acceptance criteria, ascertain that they are appropriate and can be met in production, and then approve them. It is often necessary, after production, to see if changes are needed. An acceptance limit that is too strict increases cost, but one that is too lax can contribute to failure to meet service requirements.

Fracture mechanic can be used to establish acceptance limits for critical parts, because it describes product performance in terms of the size of any flaw that might be present and can aid in establishing whether in-service inspection is necessary. Fracture mechanics studies usually are undertaken only for critical parts because such studies are exacting and expensive. Inspection criteria should include probability/confidence limits for the inspection procedure because it is not the smallest defect that must be detected, but the largest defect that might be missed that ultimately determines the reliability of a part (also see Sections 5.4.2.7, 7.3 and 7.4).

5.4.3.4 Inspection standards

Inspection standards should be established so that decisions to accept/rework or scrap parts are based on the probable effect that a given defect will have on the service life or product safety. Once such standards are established non-destructive inspection can characterise flaws in terms of a real effect rather than on an arbitrary basis that may impose useless or redundant quality requirements.

Most non-destructive inspection methods rely on a reference standard to define acceptance limits or to estimate defect sizes. However there often is no recognised universal standard that can be used on diverse products or to satisfy varying inspection requirements of individual users. For instance ultrasonic inspection is widely used to inspect adhesive bonded structures, yet the variety of designs, materials and adhesives that are used do not permit a standard reference panel that is universally acceptable to be produced. Under normal circumstances, producer and consumer agree in advance as to the design of the reference standard and to the procedure for using it.

5.4.3.5 Effect of manufacturing operations

It is difficult to define the best point in a sequence of manufacturing operation at which inspection should be performed. Obviously, there should be some type of final inspection after all manufacturing operations have been completed. However, final inspection is often far from optimal as regards either quality of inspection or

overall economy of manufacture. In many instances it is easier, more reliable and more economical to perform limited inspection at each of several points in the manufacturing sequence rather than performing all inspections at the end of the sequence. In general, the principles listed below should be followed when choosing the point of inspection:

(i) Inspect raw material for flaw that may have been missed by the supplier's inspection and that can interfere with manufacturing operations or will reduce performance of the finished part.

(ii) Perform intermediate inspection following each operation or series of operations that have a significant probability of introducing serious flaws.

(iii) Perform intermediate inspection when the part shape affords easiest access to the region to be examined.

(iv) Limit the extent of non-destructive inspection to detection of flaw having a size, type and location that will significantly affect subsequent manufacturing operations or service performance.

(v) Use different inspection methods to detect different types of flaws particularly when no single method yields an optimal balance between inspection cost and sensitivity to the various types of flaws.

(vi) Perform final non-destructive inspection only to detect those flaws that could have been introduced after the last previous inspection or to serve as a check (audit) of intermediate inspection.

Characteristically, non-destructive tests are easiest to perform and most effective when applied to incoming stock or at intermediate points in the manufacturing process rather than at final inspection. From the standpoint of manufacturing economy it is foolish to spend time and effort processing parts that already contain flaws that exceed allowable limits. Consequently it is desirable to find non-conforming parts and remove them from the normal process flow as soon as possible after the non-conformance is introduced. Of course, each set of operations will be different from all others and each situation should be studied to determine where in the manufacturing sequence non-conformance can be detected with greatest effectiveness and least cost. Point of greatest effectiveness may not coincide with points of least cost so trade-offs to achieve optimal balance may have to be made. In some instances, a highly sensitive non-destructive test method cannot be economically justified. Usually a less costly method can be substituted but with an accompanying reduction in sensitivity.

5.4.3.6 Quality manuals

A quality manual is a document which lays down the basic policies and principles on which the inspection group functions and provides the co-ordination links with the others. More detailed collections of operating procedures, resource information and data upon which the inspection group's quality depends are also

included. It is a working document describing the reality of the group's operations for use by both management and staff.

Typical elements of a quality manual are:

1. Table of contents.
2. Amendment of records.
3. Introduction.
4. Management of quality system.
5. Description of group and its function.
6. Staff.
7. Equipment.
8. Testing environment.
9. Test methods.
10. Operational procedure.
11. Control of test items.
12. Test records.
13. Diagnostic and corrective actions.
14. Test reports.
15. Subcontracting.
16. Occupational health and safety.
17. Proprietary rights and confidentiality.
18. Accreditations held.

5.4.4 Inspection

The basic definition of inspection has already been given in Section 5.2.5. Inspection is another more detailed level of quality control. The term implies the physical examination of some if not all of the product or structure after it has been completed. In general it could be expected to be more costly than for surveillance or audit, but it should also be more thorough. Inspection in welding could be the monitoring and critical examination of welding prior to, during and following completion of the weld.

Inspection may be essential in a situation where the design or service conditions of the component are so critical that the extra cost is warranted, where the purchaser has no confidence in a supplier, probably based on experience, or where the supplier has no in-house quality assurance programme. This gives rise to the concept of third party inspection where the inspection responsibility is taken up by the purchaser's agent or sometimes an independent quasiregulatory organization specializing in inspection in specific industrial fields. This agent or the organizations for inspection are, in principle, agreed to by the purchaser and the manufacturer at the time of signing the contract.

It is also useful to consider at what stage of production inspection is essential. There is the patrol inspection which many be performed any time at random. This basically is carried out for the purpose of surveillance. As the fabrication progresses some hold points are decided beyond which fabrication should not proceed unless the job has been inspected and declared acceptable. This is called

the stage inspection. Various hold-up points and the related stages of inspection should preferably be negotiated, defined and mutually agreed to. Last of all is the final inspection which is carried on the completed or finished product.

Inspection is carried out by following definite inspection steps or schedules as properly documented in an inspection plan which should be prepared for each job. The objective of the inspection plan is to indicate the extent and timing of the inspection action which should be taken to ensure that production does not proceed before inspection is complete while the components are accessible.

While there is no standard inspection plan, most are designed to provide not only a schedule of operations for the guidance of process and inspection personnel but also to serve as documentary evidence that the various operations have been performed. The inspection plan must start with action items that should occur before welding even begins. It should begin with a thorough review of the purchasing documents because quality is defined as "conformance to requirements", and a surprising number of rejects are still due to requirements being set incorrectly, with the incorrect acceptance criteria, unrealistic workmanship standards or inadequate consideration for the end use. Inspection of incoming materials for assessing condition and also for checking conformance to specifications is usually a part of the inspection plan. There are many cases documented where failure was due to an incorrect material being supplied or selected from the store room shelf.

Observation of fit-up, weld preparation and cleaning are critical prior to the welding operation. The inspector has a responsibility to ensure that only appropriately qualified people are working on the job. The actual welding operation might be observed to ensure compliance with the procedure and to know if the welder is familiar with the procedure.

The product may require examination after welding and before painting. The inspection plan should detail this if required. For the producer, the inspection plan indicates the points beyond which he cannot proceed without having the inspector present (for example, to witness a hydrostatic test).
The inspection plan will tell the inspector the level of inspection required, for example, does he need to witness an operation or simply satisfy himself that the operation has been done and documented.

It might be argued that every production worker has a responsibility to exercise his own "quality control" by inspecting his own work. In fact this is usually done on an ongoing basis by the manufacturer's own staff. But it is well known that a trained objective observer might be more sensitive to production faults than the person closest to them. It is useful, therefore, to recognise that there are some specific duties for "inspectors" that will vary from plant to plant, contract to contract and product to product. These specific duties might overlap for a given project. However, as long as the respective inspectors do not lose sight of their own responsibilities and loyalties, little difficulty occurs. ASME boiler and pressure vessel code refers frequently to the "authorized inspector" who has some distinct responsibilities and functions to perform. The term inspection is then

reserved for functions carried out by this individual. Article 1 of ASME Section V defines the duties of authorized inspector as follows: the inspector concerned with the fabrication of the vessel or pressure part shall have the duty of verifying to his satisfaction that all examinations required by the referencing code section have been made to the requirements of this section and the referencing code section. He shall have the right to witness any of these examinations to the extent stated in the referencing code section.

While largely determined by a contract document and reporting relationships, the inspector's duties and responsibilities are generally to assure that the product conforms to the specification. He must use all of the appropriate methods available to him to support his assurance. He must have a good working relationship with production staff, but he must never lose sight of his quality objective.

5.5 QUALITY ASSURANCE

Quality assurance has already been defined in Section 5.2.3. A quality assurance system is an effective method of attaining and maintaining the desired quality standards. It is based on the fact that quality is the responsibility of the entire organization and that inspection alone does not assure quality or more precisely, does not assure conformance to requirements of the control or customer order. This applies not only to complex products such as satellites or nuclear submarines, but also to simple products such as nails or pipe fittings. Regardless of the product or service involved, the essentials of an effective quality assurance system include:

1. Independence of the quality assurance department from the design and production departments.
2. Standards of quality that reflect both the needs of the customer and the characteristics of the manufacturing process.
3. Written procedures that cover all phases of design, production, inspection, installation and service, with a programme for continuous review and update of these procedures.
4. Control of the flow of documents such as order entry, order changes, specifications, drawings, route slips, inspection tickets and shipping papers.
5. Methods for maintenance of part identity which must establish traceability through the process.
6. Methods for timely detection and segregation of non-conforming material which must also include programmes for corrective action.
7. Schedules for periodic calibration of inspection equipment.
8. Schedules for retaining important records.
9. Programmes for training and qualification of key production and inspection personnel.
10. Systems for control of specifications incorporated into purchase order; for control of the quality of purchased goods and for appropriate inspection of purchased goods.

11. Systems for control of manufacturing, assembly and packaging processes, including inspection at key points in the process flow.

12. A system for periodic audit of any or all of the above by persons having no direct responsibility in the area being audited.

The quality assurance system is an evaluation or audit of each one of these subsystems to determine how effectively the functions are being performed. Evaluations are usually conducted each year to determine which elements and subsystems need improvement. The overall rating provides a comparison with past performance or with other plants of a multiplant corporation. These subsystems are briefly described in the following sections.

5.5.1 Independence of quality assurance department

Responsibility for the development, operation and monitoring of an effective quality assurance programme in a plan usually rests with the quality assurance manager. Companies having several plants may have a corporate quality assurance department that reviews and co-ordinates the system for the entire organization. To be effective this should be an independently staffed department that reports directly to an upper level manager such as general manager, vice president or president. The quality assurance department should be free to devise and recommend specific systems and procedures and require corrective action at their discretion.

5.5.2 Establishment of quality standards

No single quality level is necessary or economically desirable for universal use; the quality requirements of a paper clip are obviously quite different from those of a nuclear reactor. Many professional groups, trade associations and government agencies have established national codes and standards. However these codes and standards generally cover broad requirements, whereas a set of detailed rules for each product or class of products is required for the control of quality.

In most plants it is the responsibility of the quality assurance manager to interpret national codes and standards in terms of the purchase order and from these to devise process rules uniquely suited to the specific products and manufacturing methods used in that particular plant. The set of process rules thus devised may be known by various names: in these training notes it will be called an 'operating practice description'. There may be thousands of operating plant descriptions in plant files, each varying from the others as dictated by code or customer requirements, limits on chemical composition or mechanical properties, or other special characteristics. Large plants may have computerised storage systems permitting immediate retrieval of part or all of the operating practice descriptions at key locations throughout the plant.

5.5.3 Written procedures

Written procedures are of prime importance in quality assurance. Oral instructions can be inadequately or incorrectly given and thus misunderstood and incorrectly

followed. Clear and concise written instructions minimise the likelihood of misinterpretation. Vague generalisations that do neither assign specific responsibilities nor determine accountability in case of error must be avoided. For instance, procedures should be specific regarding the type and form of inspection records, the identity of the individual who keeps the records and where the records are kept. Similarly, a calibration procedure should not call for calibration at 'periodic intervals' but should specify maximum intervals between calibrations. Depending on the type of equipment, calibration may be performed at intervals ranging from a few hours to a year or more.

5.5.4 Control of document flow

The original purchase order, which is often less than one page in length, may generate hundreds of other working papers before the ordered material or part is shipped. All paperwork must be accurate and must reach each work station on time. In some industries where there may be an average of two or more specifications or drawing changes per order, an effective system of material tracking that is separate and distinct from material identification is necessary.

Control of document flow places direct responsibility on departments not usually associated with quality control. The sales office (which is responsible for entry of the customer order), the production planning group (which is responsible for scheduling work and tracking material) and the accounting department (which is responsible for billing and shipping) are all involved. Many large plants have computerised order systems, the heart of which is an 'active order file'. This computer file receives periodic inputs to update information on specifications, drawings, material sizes, shop operations, shipping and routing. In turn this file may be accessible from various terminals in the sales office, home office or plant, when information is needed on material location, order status and the like.

5.5.5 Maintaining identity and traceability of materials

In high speed manufacturing operations, particularly those involving hot work, identity markings on the raw material (such as paint mark, stencils or stamps) are usually destroyed during processing. In such instances, procedures must be devised for maintaining identity not by marking alone but also by location and count. These procedures sometimes must provide for traceability of individual units of products by a method suitable for the product and process and must include any additional identity that the customer may require. Ultimately both producer and customer must be confidant that the goods actually delivered are described accurately in the shipping papers, test reports and certificates of compliance. This confidence is of great importance in certain applications in the aerospace and nuclear industries.

5.5.6 Non-conforming material and corrective action

A system for detection and segregation of non-conforming material requires:

(i) Written inspection instructions that can be clearly understood.

(ii) Identified, segregated holding areas for parts that have been rejected.

(iii) A structured group (sometimes called a materials review board) to evaluate rejected material, make final judgement on its fitness for use, decide what is to be done with non-conforming material and prescribe action for the cause of rejection.

In many instances rejected parts are only slightly out of tolerance and their usefulness is not impaired. Even so, all decisions of a materials review board to accept non-conforming material must be unanimous. In the absence of unanimity, the problem may be referred to top management for a decision based on overall business judgement. In some companies, the authority of the materials review board is limited to merely deciding whether or not non-conforming material is fit for use. However, in many companies the board also determines what is to be done with non-conforming lots; whether they are to be shipped 'as is', sorted, repaired or scrapped, and fixes the accountability for incurred losses. When corrective action is recommended by a materials review board, it is usually systems oriented, that is, intended to prevent recurrence of the non-conformity by avoiding its cause. In instances where a lot has been rejected because the acceptance number for a sampling plan has been exceeded, decisions concerning disposition of the lot often are made on the basis of costs, the solution that results in the least total cost to both producer and customer is adopted. Sometimes, material that is slightly out of tolerance and therefore not fit for use by one customer may meet the specifications of another customer.

5.5.7 Calibration of equipment

The quality assurance system must recognise that the accuracy and repeatability of measuring and testing equipment may be affected by continued use; maximum intervals between calibrations should be specified in the written quality assurance procedures. Except perhaps for small hand instruments such as micrometers, each testing machine or instrument should be plainly labelled with the last date of calibration. Calibration standards should be traceable to recognised industry or national standards of measurement. It is also desirable to maintain a central file of calibration records for each plant or department.

5.5.8 Retention of records

A quality assurance system must designate which records are to be retained and must set down minimum time periods for retention of such records. It is usual for important documents to be retained for 25 years or more; the nuclear industry is required to maintain records for 40 years. Retention time, however, should be consistent with real needs as dictated by projected lifetime of products or by legal requirements. Besides satisfying certain contractual or other legal requirements, retained records can provide important cost benefits to both producer and customer. In one instance, extensive and costly testing of a 50 years old structure prior to repair was avoided when the fabricator was able to produce original drawing and material test reports.

5.5.9 Personnel training and qualification

National codes exist for the qualification of certain specialised workers, for instance welders and inspectors. When applicable, codes should be incorporated as minimum requirements for training and qualification of key personnel. All of these, however, must be supplemented by local written procedures for both on-the-job and classroom training. Quality assurance management must reduce complex procedures to the simplest form that will permit a trainee to understand exactly what the job is and how it is to be performed.

5.5.10 Control of purchased material

All specifications and orders for outside purchases of material whose performance may affect product quality should be subject to approval by quality assurance management. Inspection of incoming material should be subject to approval by quality assurance management. Inspection of incoming material should be incorporated into the quality assurance programme. The main purpose of receiving inspection is to check for failures of vendor quality programmes, but receiving inspection should not be expected to compensate for poor quality control by vendors. The purchaser should evaluate and periodically audit the quality assurance system of each major supplier to make sure that the purchased material can be expected to have the specified level of quality.

5.5.11 Manufacturing, assembly and packaging

All manufacturing, assembly and packaging processes should be controlled to ensure attainment of the finished product of the right quality at the time of its reaching the customer. Design drawings and the processes of manufacturing and assembly should be assessed whether appropriate methods of adequate capability and sensitivity are being applied and whether the results being obtained are reliable and reproducible or not. The tests should be applied at appropriate stages during manufacture and all test reports should be properly signed by authorized persons. All manufacturing, testing, assembly and packing should be done according to verifiable written procedures.

5.5.12 Quality audit

Quality audit is an independent evaluation of various aspects of quality performance to provide information with respect to that performance. Quality audits are usually made by companies to evaluate their own quality performance, by buyers to evaluate the performance of their vendors, by regulatory agencies to evaluate the performance of organizations which they are assigned to regulate.

Purpose of audit is to provide assurance that:

- procedures for attaining quality are such that, if followed, the intended quality will be obtained.
- products are fit for use and safe for the user.

- laws and regulations are being followed.
- there is conformance to specifications.
- written procedures are adequate and being followed.
- the data system is able to provide adequate information on quality
- corrective action is being taken with respect to deficiencies.
- opportunities for improvements are identified.

For an internal quality audit typically the organization is divided up into its component parts and each area is audited. The time taken depends on the size of the organization. For a small NDT organization one could audit the following:

- documentation of NDT procedures.
- control of stores.
- receipt of job instructions.
- purchasing of equipment and accessories.
- maintenance of equipment and accessories.
- calibration of equipment.
- contract administration.
- safety.
- accounting
- office administration, e.g. wages, leave, superannuation.
- organizational structure.
- research and development.
- reports and records.

A periodic audit of quality of the system performance against written standard is needed to detect corner-cutting, non-compliance and intentional violations of established quality procedures. To be as unbiased as possible, such audits should be performed by persons not having responsibility in the area being audited. In companies having multiple plants, each individual plant may conduct its own internal audit, but in addition should be subject to audit by corporate staff personnel. The most important activities of corporate staff aside from auditing are review of the quality system with the highest level of plant management and follow up to approve corrective action for any discrepancies found during an audit.

Periodic review of the quality assurance system and reaffirmation of quality objectives by top management should be part of company policy. This will in part ensure long range viability of the business enterprise.

6. CODES AND STANDARDS AND THEIR IMPORTANCE IN NDT

6.1 THE NEED FOR STANDARDS

6.1.1 Variables in NDT

The objective of most non-destructive testing methods is to detect internal defects with respect to their nature, size and location. This is done by different methods depending upon their inherent capability or sensitivity to flaw detection. A method is said to have a good or high sensitivity of flaw detection when it can detect relatively smaller flaws and vice versa. The sensitivity of flaw detection for different NDT methods depends upon a number of variable factors as given below:

6.1.1.1 Penetrant testing

(i) Type of specimen, its geometry and surface condition.
(ii) Nature, type and location of defects.
(iii) Type of dye penetrants, their colour and viscosity.
(iv) Method of application of penetrants, residence time.
(v) Method of cleaning, both before and after the application of penetrant.
(vi) Type of developer, its fineness of grain size and its mobility, the contrast it provides with the penetrant used.
(vii) Black light and general viewing conditions
(viii) Operator's eyesight, qualifications and experience.

6.1.1.2 Magnetic particle testing

(i) Type of specimen, its geometry, shape and surface condition.
(ii) Nature and type of defects.
(iii) Method and level of magnetization.
(iv) Contrasting agents properties.
(v) Properties of magnetic particles such as colour, size and viscosity of particle sand fluid.
(vi) Viewing conditions and lighting arrangements, etc.
(vii) Operator's qualifications, skill and experience.

6.1.1.3 Eddy current testing

(i) Type of specimen, its geometry, shape, composition, conductivity and surface condition.
(ii) Nature, location and type of defects.
(iii) Probe characteristics such as frequency and impedance.
(iv) Equipment characteristics, for example, impedance type or phase type.
(v) Calibration of equipment using defect free and known-defects specimens.
(vi) Interpretation of results; operator's qualifications, skill and experience.

6.1.1.4 Radiographic testing

(i) Type of specimen, its geometry, shape, thickness, density and surface condition.
(ii) Nature, type and location of defects; radiographic appearance of typical defects.
(iii) Exposure conditions such as energy of radiation, s.f.d, o.f.d., source size, filters (if used), IQIs.
(iv) Types of films and film processing (development, fixing, drying, etc.).
(v) Film viewing conditions, lighting, operator's eyesight.
(vi) Interpretation of results; operator's qualifications, skill and experience.

6.1.1.5 Ultrasonic testing

(i) Type of specimen, its geometry, shape and surface condition.
(ii) Nature, type and location of defects.
(iii) Probe characteristics such as frequency, beam spread, near zone.
(iv) Couplant characteristics such as acoustic impedance, viscosity, wettability.
(v) Equipment characteristics, range and resolution, pulse shape, etc.
(vi) Equipment calibration, procedure and calibration blocks.
(vii) Scanning procedure.
(viii)Interpretation of results; operator's qualifications, skill and experience.
(ix) Recording, evaluation and reporting.

6.1.2 Process of standardization

Imagine that someone is to perform, say, radiography of circumferential welds in steel pipes of 50 cm diameter having a 10 cm wall thickness. He will undertake extensive experimentation to establish the values of different variable factors as listed under radiographic testing in Section 6.1.1.4 to evolve a method which gives reliable and reproducible results of desired sensitivity. This person is wise enough to carefully write down his procedure for testing of pipe welds. If someone else anywhere had a problem of radiographically inspecting pipe welds of similar specifications, there would be two options open to him. First he could undertake all the extensive experimentation involving lot of time, effort and money and second he could request the first person and use his procedure which was known to be giving reliable and reproducible results of desired sensitivity. Many persons in one city, country or different countries could use this method as a guide or recommended procedure or practice. These many persons might sometimes get together in a meeting, conference or a committee to exchange their views and experience related to this procedure. They might mutually agree on a standard procedure for radiographic testing of circumferential welds in steel pipes of 50 cm diameter and 10 cm wall thickness and recommend it to the standard issuing authority of their country to issue this as a national standard. Some such standards issued by the standard issuing authority of the country could be taken up by the legislature or parliament of the country and their use made obligatory by law. This briefly explains in very simple terms the otherwise complex and time consuming process of formulation and issuance of codes and standards.

6.1.3 Aims of standardization

6.1.3.1 Clear communication

Written standards make it easy for the customer or user to communicate with the producer. Specifying that magnetic particle inspection shall comply with ASTM E 709 leaves the producer with a clear understanding of the technology required.

6.1.3.2 Economy of effort

The purchaser or designer may have a general idea of what is required (and what is available) for a desired level of inspection. If all of the possible parameters and variables are detailed in a document, already prepared by experts in the field and published as a standard, then he is saved the effort of preparing every thing himself.

6.1.3.3 Minimum performance

Published codes and standards accepted by industry in general, provide the regulator or the purchaser with confidence that the product or service will at least perform to the level detailed in the standard.

6.1.3.4 Historical record

After the product has gone into service (sometimes years after) a life record of the standard used for production or inspection will likely be sufficient documentation of the process used to produce it.

6.1.3.5 Collective wisdom

A standard, developed by the consensus process, involves technical experts from the producers, the users and the general public (perhaps represented by a regulatory body). In addition to ensuring that all interests are represented, this process draws in the best technical knowledge on every side, and through discussion and debate, results in a document based on the collective wisdom of the participants.

6.1.3.6 International co-operation

Standards can play an important role in international co-operation when their use is made in negotiating international contracts and treaties for the supply of goods and services by one country to another. They help in the establishment and increase in the trade relations between countries by the removal of trade barriers caused by differences in national practices. The clauses of incentives and penalties between the countries and the multinational companies are usually negotiated with reference to standards and related clauses of contracts. Standards play a vital role in purchasing and selling goods between various countries as they help in defining the quality as well as accept/reject criteria for these goods. Uniformity of standards between countries or the use of the same standard helps promote

understanding between the people of these countries. It also facilitates travel and working of the people between these countries.

6.1.3.7 Improvement in the quality of life

Standards are helpful in the repetitive production of "good quality" products. This has a direct effect on the quality of life. This may mean better clothing; better food; better houses and household items; travel in better and safer automobiles, trains, ships and aircraft, better medicines and health care, better offices and office equipment and lastly a better, cleaner and safer environment, all through the proper use of appropriate standards.

6.2 DIFFERENT CATEGORIES OF STANDARDS

6.2.1 Guides and recommended practices

Guides and recommended practices are standards that are offered primarily as aids to the user. They use verbs such as "should" and "may" because their use in usually optional. However, if these documents are referenced by codes or contractual agreements, their use may become mandatory. If the codes or agreements contain non-mandatory sections or appendices, the use of referenced guides and recommended practices by them, are at the user's discretion.

6.2.2 Standards

Standards are documents that govern and guide the various activities occurring during the production of an industrial product. Standards describe the technical requirements for a material, process, product, system or service. They also indicate as appropriate, the procedures, methods, equipment or tests to determine that the requirements have been met.

6.2.3 Codes and specifications

Codes and specifications are similar types of standards that use the verbs "shall" or "will" to indicate the mandatory use of certain materials or actions or both. Codes differ from specifications in that their use is mandated with the force of law by governmental jurisdiction. The use of specifications becomes mandatory only when they are referenced by codes or contractual documents. A prime example of codes is the ASME boiler and pressure vessel code which is a set of standards that assure the safe design, construction and testing of boilers and pressure vessels.

6.2.4 Standardization

Standardization of a process can be defined as the setting up of process parameters so that it constantly produces a product of uniform characteristics.

6.3 TYPES OF STANDARDS

6.3.1 Standards for terminology

These standards are essential for avoiding failure to reach an agreement between the user and purchaser of the NDT services. Some of such standards are:

a)	Appendix- A of ASME boiler and pressure vessel code (B & PV)-95	Glossary of terms used in non-destructive testing.
b)	DIN 54 119-81	Terms and concepts in ultrasonic inspection.
c)	BS 3683-84	Glossary of terms used in non-destructive testing.
d)	ASTM E-500-74 ultrasonic	Standard definitions of terms relating to inspection.

6.3.2 Standards for equipment

A prerequisite to standardization of inspection techniques is a regularized method of ensuring that the equipment in use is either inherently capable of or can be adjusted to give a certain predetermined degree of sensitivity and performance. Some of the standards of this type are:

a)	ISO-2400-72	Welds in steel-reference block for the calibration of equipment for ultrasonic testing.
b)	JIS Z-2348-78	Calibration block (type A 2) used in ultrasonic testing.
c)	BS 5650-78	Specification for apparatus for gamma radiography.
d)	IIS/IIW 278-67	Recommended procedures for the determination of certain ultrasonic pulse echo characteristics by the IIW calibration block.
e)	ASTM E-428-92	Practice for fabrication and control of steel reference blocks used in ultrasonic inspection.
f)	ASME B & PV Code-95	Section V (Articles 1, 4, 5 & 23).

6.3.3 Standards for testing methods

These standards, usually, entitled as "recommended practice" or "method" are issued in order to select an optimal test technique for a particular job. In other words these will help in selecting a technique which reveals only those defects

which may be considered harmful without giving prominence to secondary features. Some of the standards of this type are:

a)	BS 3923-78	Methods for ultrasonic examination of welds.
b)	JIS G 0801-74	Ultrasonic examination of steel plates for pressure vessels.
c)	ISO 5948-81	Railways rolling stock material; ultrasonic acceptance testing.
d)	DIN 54125 -82	Ultrasonic testing of welded joints.
e)	ASTM E-164-94	Practice for ultrasonic contact examination of weldments.
f)	ASME B & PV Code-95	Section V (Articles 1, 4, 5, & 23).

6.3.4 Standards for education, training and certification of NDT personnel

To avoid unreliable results of an NDT examination besides using standardized equipment and test methods, the persons carrying out the examination must also be properly educated, trained and certified in the method. Various standards are available to cater for this requirement. Lately there is an effort to harmonize the education, training and certification. Some of the standards of this type are:

a)	DIN 54160-78	Requirements for non-destructive testing personnel.
b)	IIS/IIW-589-79	Recommendations relating to the training of non-destructive testing personnel.
c)	ISO 9712-92	Non-destructive testing-qualification and certification of personnel.
d)	ASNT-SNT-TC-IA (86)	Recommended practice for non-destructive testing personnel qualification and certification.
e)	BS EN 473-93	General principles for qualification and certification of NDT personnel.

6.3.5 Standards for acceptance and rejection

After the defects have been investigated by NDT in terms of their nature, size and location, it is important to evaluate their acceptance or rejection. This is done with the help of standards, some examples of which are the following:

a)	ASTM E 125-93	Reference photographs for magnetic particle indications on ferrous castings.

b)	ASTM E 186-93	Standard reference radiographs for heavy walled steel castings.
c)	BS 5500-94	Specification for unfired fusion welded pressure vessels.
d)	JIS Z 3104-68	Methods of radiographic test and classification of radiographs of steel welds.
e)	ASTM E 390-91	Standard reference radiographs for steel fusion welds.

6.3.6 Accreditation standards

These standards help in judging the capability and suitability of NDT laboratories and institutions for undertaking different types of NDT work including education and training of NDT personnel. Examples are:

a)	ASTM-E 543-93	Practice for evaluating agencies that perform non-destructive testing.
b)	European Union standard EN 45002	General criteria for the assessment of testing laboratories.
c)	EN 45013 operating	General criteria for certification bodies schemes for certification of personnel.
d)	ASTM E 994	Guide for laboratory accreditation systems.

6.4 SOME STANDARD ISSUING BODIES AND SOME OF THEIR STANDARDS RELATED TO NDT

6.4.1 International Organization for Standardization (ISO)

ISO/1027-86	Radiographic image quality indicators for non-destructive testing — Principles and identification
ISO 1106	Recommended practice for radiographic examination of fusion welded joints
Part 1-84	Fusion welded butt joints in steel plates upto 50 mm thick
Part 2-85	Fusion welded joints in steel plates thicker than 50 mm and up to and including 200 mm in thickness
Part 3-84	Fusion welded circumferential joints in steel pipes up to 50 mm wall thickness
ISO-2178	Non-magnetic coatings on magnetic substrates — Measurement of coating thickness — Magnetic methods

ISO 2360-82	Non-conductive coatings on non-magnetic basis metals - Measurement of coating thickness — Eddy current method
ISO 2361-82	Electrodeposited nickel coatings on magnetic and non-magnetic substrates — Measurement of coating thickness
ISO 2400-72	Welds in steel-reference block for the calibration of equipment for ultrasonic examination.
ISO 2437-72	Recommended practice for the X ray inspection of fusion-welded butt joints for aluminium and its alloys and magnesium and its alloys 5–50 mm thick.
ISO 2504-73	Radiography of welds and viewing conditions for film utilization of recommended patterns of image quality indicators (IQI).
ISO 3458-76	Assembled joints between fittings and polyethylene (PE) pressure pipes — Test of leakproofness under internal pressure
ISO 3503-76	Assembled joints between fittings and polyethylene (PE) pressure pipes — Test of leakproofness under internal pressure
ISO 3777-76	Recommended practice for the radiographic inspection of resistance spot welds for aluminium and its alloys.
ISO 3879-77	Recommended practice for liquid penetrant testing of welded joints.
ISO 3882-86	Metallic and other non-organic coatings — Review of methods of measurement of thickness
ISO 3058-74	Non-destructive testing — Aids to visual inspection — Selection of low-power magnifiers
ISO-3059-74	Non-destructive testing — Method for direct assessment of black light sources.
ISO-3452-84	Non-destructive testing — Penetrant inspection — General principles.
ISO-3453-84	Non-destructive testing — Liquid penetrant inspection — Means of verification
ISO 3999-77	Apparatus for gamma radiography, specification.
ISO-4386	Non-destructive testing
Part 1–92	Ultrasonic testing of bond in metallic multilayer plain bearings
Part 3-92	Non-destructive testing — Penetrant testing of metallic multilayer plain bearings
ISO 4986-92	Steel castings — Magnetic particle inspection
ISO 4987-92	Steel castings — Penetrant inspection
ISO 4993-87	Steel castings — Radiographic inspection
ISO 5576-83	Industrial radiology — Non-destructive testing — Vocabulary

ISO 5579-85	Non-destructive testing — Radiographic examinationi of metallic materials by X and gamma rays — Basic rules
ISO 5580-85	Non-destructive testing — Industrial radiographic illuminators — Minimum requirements
ISO 5655-93	Photography — Film dimensions — Industrial radiography
ISO 5948-81	Railway rolling stock material-Ultrasonic acceptance testing
ISO 6933-86	Railway rolling stock material — Magnetic particle acceptance testing
ISO 7004-87	Photography — Industrial radiographic film — Determination of ISO speed and average gradient when exposed to X and gamma radiation
ISO 7963-85	Welds in steel — Calibration block No. 2 for ultrasonic examination of welds
ISO 9302-89	Seamless and welded (except submerged arc-welded) steel tubes for pressure purposes — Electromagnetic testing for verification of hydraulic leak tightness
ISO 9303-89	Seamless and welded (except submerged arc-welded) steel tubes for pressure purposes — Full peripheral ultrasonic testing for the detection of longitudinal imperfections
ISO 9304-89	Seamless and welded (except submerged arc-welded) steel tubes for pressure purposes - Eddy current testing for the detection of imperfections.
ISO 9305-89	Seamless steel tubes for pressure purposes — Full peripherial ultrasonic testing for the detection of transverse imperfection.
ISO 9402-89	Seamless and welded (except submerged arc-welded) steel tubes for pressure purposes. Full peripherical magnetic transducer/flux leakage testing of ferromagnetic steel tubes for the detection of longitudinal imperfection
ISO 9583-93	Non-destructive testing - Liquid penetrant inspection of metallic surgical implants.
ISO 9584-93	Non-destructive testing - Radiographic examination of cast metallic surgical implants
ISO 9598-89	Seamless steel tubes for pressure purposes - Full peripherical magnetic transducer/flux leakage testing of ferromagnetic steel tubes for the detection of transverse imperfections
ISO 9712-92	Non-destructive testing — Qualification and certification of personnel
ISO 9764-89	Electric resistance and induction welded steel tubes for pressure purposes — Ultrasonic testing of the welded seam for the detection of logitudinal imperfections
ISO 9765-90	Submerged arc-welded steel tubes for pressure purposes - Ultrasonic testing of the weld seam for the detection of longitudinal and/or transverse imperfections

ISO 9915-92	Aluminium alloy castings — Radiography testing
ISO 9916-92	Aluminium alloy and magnesium alloy castings — Liquid penetrant inspection.
ISO 9935-92	Non-destructive testing — Penetrant flaw detectors — General technical requirements
ISO 10042-92	Arc-welded joints in aluminium and its weldable alloys — Guidance on quality levels for imperfections
ISO 10049-92	Alumium alloy castings — Visual method for assessing the porosity
ISO 10124-94	Seamless and welded (except submerged arc-welded) steel tubes for pressure perposes — Ultrasonic testing for the detection of laminar imperfections
ISO 10332-94	Seamless and welded (except submerged arc-welded) steel tubes for pressure purposes — Ultrasonic testing for the verification of hydraulic leak tightness
ISO 10543-93	Seamless and hot-stretch-reduced welded steel tubes for pressure purposes — Full peripheral ultrasonic thickness testing
ISO 11496-93	Seamless and welded steel tubes for pressure purposes — Ultrasonic testing of tube ends for the detection of laminar imperfections
ISO 12094-94	Ultrasonic testing for the detection of laminar impefections in strips/plates used in the manufacture of welded tubes
ISO 12095-94	Seamless and welded steel tubes for pressure purposes — Liquid penetrant testing.

6.4.2 International Institute of Welding (IIW)

IIS/IIW-127-64	Behaviour of ultrasonic waves in the presence of various defects in welds.
IIS/IIW-183-65	Recommendations for determination of focal spot size of X-ray tubes.
IIS/IIW-205-66	Draft recommended practice for the ultrasonic inspection of butt welds.
IIS/IIW-278-67	Recommended procedure for the determination of certain ultrasonic pulse-echo equipment characteristics by the IIW calibration block.
IIS/IIW-310-68	Limitations inherent in the use of ultrasonic for the examination of welds.
IIS/IIW-450-74	Calibration Block No 2' for ultrasonic examination of welds.

IIS/IIW-184-65 Recommendation concerning sensitometric test on radiographic films without screens or with lead screens.

IIS/IIW-185-65 Rules for the reading of the IQI recommended by Commission V.

IIS/IIW-208-66 Report on the investigation into the influence of the plate thickness on the visibility of weld defects and on image quality in the radiography of welds.

IIS/IIW-275-67 Draft recommended practice for the examination with X-rays of resistance spot welds in aluminium and its alloys.

IIS/IIW-412-72 *The use and limitations of radiographic image quality* indicators.

IIS/IIW-359-70 Detection of sub-surface defects in welds using magnetic particle methods.

IIS/IIW-423-73 Recommended practice for the radiographic examination of fusion-welded butt joints in steel plates from 0.5 to 50 mm thick.

IIS /IIW-424-73 Image quality indicators for use in the radiography of aluminium and its alloys in thickness upto 50 mm.

IIS/IIW-492-75* Recommended practice for radiographic inspection of fusion-welded circumferential joints in steel pipes from 1 mm up to 50 mm thickness

*(Revision of IIS/IIW-36-59)

IIS/IIW-572-78 Final report of the image quality indicator developed by the CERL (Central Electricity Generating Board, UK).

IIS/IIW-636-80 Inspection of welds when fitness-for-purpose criteria are applied — Preliminary recommendation.

IIS/IIW-642-80 Investigation of the through-thickness properties of thick plate for welded constructions.

IIS/IIW-675-81 Ultrasonic techniques for the quantitative evaluation of weld defects and their limitations.

6.4.3 British Standards Institution (BSI)

BS O A standard for standards.

Part 1-91 Guide to general principles of standardization.

Part 2-91 Guide to BSI committee procedures.

Part 3-91 Guide to drafting and presentation of British Standards.

BS 499 Welding terms and symbols.

Part 1 -91 Glossary of welding, brazing and thermal cutting.

Part 1

Supplement-92
Definitions for electric welding equipment

Part 2-89 Specification for symbols for welding (Partially replaced by BSEN 24063-92)

Part 2c-80 Welding symbols

BS 600-93 The application of statistical methods to industrial standardization and quality control.

BS 2600 Radiographic examination of fusion welded butt joints in steel.

Part 1-83 Methods for steel 2 mm upto and including 50 mm thick.

Part 2-73 Methods for steel over 50 mm upto and including 200 mm thick.

BS 2704-83 Specification for calibration blocks for use in ultrasonic flaw detection.

BS 2737-85 Terminology of internal defects in castings as revealed by radiography.

BS 2910-86 Methods for radiographic examination of fusion-welded circumferential butt joints in steel pipes.

BS 3451-81 Methods of testing fusion welds in aluminium and aluminium alloys

BS 3683 Glossary of terms used in non-destructive testing.

Part 1-85 Penetrant flaw detection.

Part 2-85 Magnetic particle flaw detection.

Part 3-84 Radiological flaw detection

Part 4-85 Ultrasonic flaw detection.

Part 5-89 Eddy-current flaw detection.

BS 3889 Methods for non-destructive testing of pipes and tubes.

Part 1-90 Methods of automatic ultrasonic testing for the detection of imperfections in wrought steel tubes

Part 2A-91 Automatic eddy-current testing of wrought steel tubes.

Part 2B-87 Eddy-current testing of non-ferrous tubes.

BS 3890-65 General recommendations for the testing, calibration, and processing of radiation monitoring films.

BS 3915-65 Specification for carbon and low alloy steel pressure vessels for primary circuits of nuclear reactors.

BS 3923 Methods for ultrasonic examination of welds.

Part 1-86 Methods for manual examination of fusion welds in ferritic steels.

Part 2-72 Automatic examination of fusion-welded butt joints in ferritic steels.

BS 3971-85 Specification for image quality indicators for industrial radiography (including guidance on their use).

BS 4031-66 Specification for X-ray protective lead glasses.

BS 4069-82 Specification for magnetic flaw detection inks and powders.

BS 4080 Specification for severity levels for discontinuities in steel castings.

Part 1-89 Surface discontinuities revealed by magnetic particle flaw detection

Part 2-89 Surface discontinuities revealed by penetrant flaw detection

BS 4094 Recommendation for data on shielding from ionizing radiation.

Part 1-88 Shielding from gamma-radiation.

Part 2-88 Shielding from X-radiation.

BS 4124-91 Methods for ultrasonic detection of imperfections in steel forgings

BS 4206-67 Methods of testing fusion welds in copper and copper alloys.

BS 4208-67 Specification for carbon and low-alloy-steel containment structures for stationary nuclear power reactors.

BS 4331 Methods for assessing the performance characteristics of ultrasonic flaw detection equipment.

Part 1-89 Overall performance: on-site methods.

Part 2-87 Electrical performance.

Part 3-87 Guidance on the in-service monitoring of probes (excluding immersion probes).

BS 1881 Testing concrete.

Part 203-86 Recommendations for measurement of velocity of ultrasonic pulses in concrete.

Part 204-88 Recommendations on the use of electromagnetic covermeters.

Part 205-86 Recommendations for radiography of concrete.

Part 206-86 Recommendations for determination of strain in concrete.

BS 6251-92 Method for determining the luminance distribution of electro-optical X-ray intensifiers.

BS 6252-92 Method for measuring the conversion factor of electro-optical X-ray intensifiers.

BSM 34-84 Method of preparation and use of radiography techniques.

BSM 36-84 Method for ultrasonic testing of special forgings by an immersion technique using flat-bottomed holes as a reference standard.

BSM 38-94 Guide to compilation of instructions and reports for the in-service non-destructive testing of aerospace products.

BSM 39-72 Method for penetrant inspection of aerospace materials and components.

BSM 40-83 Methods for measuring coating thickness by non-destructive testing.

BSM 42-83 Methods for non-destructive testing of fusion and resistance welds in thin gauge materials.

BS 6443-84 Method for penetrant flaw detection.

BS 4489-84 Method for measurement of UV-A radiation (black light) used in non-destructive testing.

BS 4513-91 Specification for lead bricks for radiation shielding.

BS 5044-87 Specification for contrast-aid paints used in magnetic-particle flaw detection.

BS 5138-88 Specification for magnetic particle flaw inspection of finished machined solid forged and drop-stamped crankshafts.

BS 5165-74 Guide to the selection of low-power magnifiers used for visual inspection.

BS 5166-74 Method for metallographic replica techniques of surface examination.

BS 5288-76 Specification. Sealed radioactive sources.

BS 5289-83 Code of practice. Visual inspection of fusion welded joints.

BS 5411 Methods of test for metallic and related coatings.

Part 3-90 Eddy-current method for measurement of coating thickness of non-conductive coatings on non-magnetic basis metals.

Part 12-90 Beta backscatter methods for measurement of coating thickness.

BS 5497 Precision of test methods.

Part 1-93 Guide for the determination of repeatability and reproducibility for a standard test method by inter-laboratory tests.

BS 5500-94 Specification for unfired fusion welded pressure vessels.

BS 5566-78 Recommendations for installed exposure rate meters, warning assemblies, and monitors for X or γ-radiations of energy between 80 keV and 3 MeV.

BS 5650-78 Specification for apparatus for gamma radiography.

BS 5884-93 Methods for the determination of relative magnetic permeability of feebly magnetic materials.

BS 5996-93 Specification for acceptance levels for internal imperfections in steel plate, strip and wide flats, based on ultrasonic testing.

BS 6072-86 Method for magnetic particle flaw detection.

BS 6208-90 Method for ultrasonic testing of ferritic steel castings including quality levels.

BS 7706-93 Guide to calibration and setting up of the ultrasonic time of flight diffraction (TOFD) technique for the detection, location and sizing of flaws.

BS 7585 Metallic multilayer plain bearings

Part 1-92 Method for non-destructive ultrasonic testing of bond.

Part 3-92 Method for non-destructive dye penetrant testing.

BS 3490-85 Specification for sizes, quantity packaging and labelling of film for industrial radiography

BS 7009-88 Guide to application of real-time radiography to weld inspection.

BS 7257-89 Methods for radiographic examination of fusion welded branch and nozzle joints in steel

BS 7534-91 Specification for radiographic cassettes

BS 7731-94 Method for radiographic examination of cast metallic surgical implants

BSEN 444-94 Non-destructive testing. General principles for radiographic examination of metallic materials by X and gamma rays

BSEN 462 Non-destructive testing. Image quality of radiographs.

BSEN 462-1-94 Image quality indicators (wire type). Determination of image quality value

BSEN 462-2-94 Image quality indicators (step/hole type). Determination of image quality value.

BSEN 473-93 General principles for qualification and certification of NDT personnel

BSEN 25580-92 Specification for minimum requirements for industrial radiographic illuminators for non-destructive testing.

BSEN 27963-92 Specification for calibration block No. 2 for ultrasonic examination of welds.

BSISO 7004-87 Photography. Industrial radiographic film. Determination of ISO speed and average gradient when exposed to X and gamma radiation.

6.4.4 Deutsches Institut für Normen (DIN)

DIN 6814-3/A2-95	Terms and definitions in the field of radiological technique
Part 3:	Dose quantities and units; Amendment A2:1994
DIN 6814-5-83	Terms and definitions in the field of radiological technique; radiation protection
DIN 8563-120-92	Quality assurance of welded structures; recommendations for arc welding of ferritic steels.
DIN 25401-8-86	Terms and definitions of nuclear technology; radiation protection
DIN 25426-1-88	Sealed radioactive sources; requirements and classification
DIN 25426-2-92	Sealed radioactive sources; special form radioactive material, requirements
DIN 25450-90	Ultrasonic equipment for manual testing
DIN 50949-84	Non-destructive testing of anodic oxidation coatings on pure aluminium and aluminium alloys by measurement of admittance
DIN 54111-1-88	Non-destructive testing; radiographic examination of metallic materials by X ray or gamma rays; radiographing of fusion welded joints
DIN 54111-2-90	Non-destructive testing; testing of metallic materials by X-rays or gamma rays; radiographic techniques for castings
DIN 54112-77	Non-destructive testing; films, exposure screens, cassettes for X-ray and gamma ray radiographs, dimensions.
DIN 54113-2-92	Non-destructive testing; radiation protection rules for the technical application of X-ray equipment up to 500 kV; general technical safety requirements and testing for the manufacture, installation and operation.
DIN 54113-3-95	Non-destructive testing, radiation protection rules for the technical application of X-ray equipment up to 500 kV- Part 3: Formulas and diagrams for the calculation of radiation protection
DIN 54115-1-92	Non-destructive testing; radiation protection rules for the technical application of sealed radioactive sources; stationary and mobile handling.
DIN 54115-3-88	Non-destructive testing; radiation protection rules for the technical application of sealed radioactive sources; organisation of radiation protection during handling and transport.

DIN 54115-4-92	Non-destructive testing; radiation protection rules for the technical application of sealed radioactive sources; construction and testing of mobile apparatus for gamma-radiography
DIN 54115-6-88	Non-destructive testing; radiation protection rules for the technical application of sealed radioactive sources; inspection, service and functional test of mobile apparatus for gamma-radiography.
DIN 54119-81	Non-destructive testing; ultrasonic inspection; terms.
DIN 54120-73	Non-destructive testing; calibration block no. 1 and its use for the adjustment and control of ultrasonic echo equipment.
DIN 54123-80	Non-destructive testing; ultrasonic method of testing claddings, produced by welding, rolling and explosion
DIN 54124-1-83	Non-destructive testing; control of properties of ultrasonic test systems; simple controls.
DIN 54125-89	Non-destructive testing; manual ultrasonic examination of welded joints
DIN 54126-1-82	Non-destructive testing; rules for ultrasonic testing; requirements for test systems and test objects.
DIN 54126-2-82	Non-destructive testing; rules for ultrasonic testing; performance of test.
DIN 54127-1-89	Non-destructive testing; calibration of ultrasonic flaw detection equipment echo height evaluation.
DIN 54130-74	Non-destructive testing; magnetic leakage flux testing, general
DIN 54131-1-84	Non-destructive testing; magnetizing equipment for magnetic particle flaw detection; fixed and mobile equipment other than hand magnets; characteristics and their determination.
DIN 54131-2-84	Non-destructive testing; magnetizing equipment for magnetic particle flaw detection; hand magnets, characteristics and their determination
DIN 54132-80	Non-destructive testing; determining the properties of test media for the magnetic particle test.
DIN 54135-90	Non-destructive testing; performance of magnetic particle tests
DIN 54136-1-88	Non-destructive testing; magnetic leakage flux testing by scanning with probes; principles

DIN 54140-1-76	Non-destructive testing; electromagnetic methods (eddy current methods), generalities
DIN 54140-2-84	Non-destructive testing; electromagnetic methods; terms
DIN 54140-3-89	Non-destructive testing; electromagnetic methods; representation and general characteristics of test coil assemblies
DIN 54141-1-82	Non-destructive testing; eddy current testing of pipes and tubes; general remarks on testing using concentric test coils and the single-frequency method
DIN 54141-2-82	Non-destructive testing; eddy current testing of pipes and tubes; reference method for the determination and calibration of the properties of an eddy current testing system using concentric test coils.
DIN 54141-3-87	Non-destructive testing; eddy current testing of pipes and tubes; procedure.
DIN 54142-1-90	Non-destructive testing; eddy current testing with probe coils; basic rules.
DIN 54142-2-90	Non-destructive testing; eddy current testing with probe coils; control of the characteristics of probe coils.
DIN 54142-3-91	Non-destructive testing; eddy current testing with probe coils; control of the characteristics of probe coils for defect detection.
DIN 54143-93	Non-destructive testing; eddy current testing; electrical characteristics of eddy current test equipment.
DIN 54150-77	Non-destructive testing; impression methods for surface examination.
DIN 54152-1-89	Non-destructive testing; penetrant inspection; procedure
DIN 54152-2-89	Non-destructive testing; penetrant inspection; verification of penetrant inspection materials.
DIN 54152-3-89	Non-destructive testing; penetrant inspection; reference blocks for determination of the sensitivity of penetrant systems
DIN 54180-1-95	Non-destructive testing - Shearography - Part 1: General principles
DIN 54180-2-95	Non-destructive testing - Schearography - Part 2: Equipment
DIN 65450-86	Aerospace; non-destructive testing; requirements for testing personnel

DIN EN 444-94	Non-destructive testing; general principles for the radiographic examination of metallic materials using X-rays and gamma-rays.
DIN EN 462-1-94	Non-destructive testing; image quality of radiographs; image quality indicators (wire type); determination of image quality values.
DIN EN 462-2-92	Non-destructive testing; image quality of radiographs; image quality indicators (step/hole type); determination of image quality values.
DIN EN 462-3-93	Non-destructive testing - Image quality of radiographs - image quality classes for ferrous metals.
DIN EN 462-4-94	Non-destructive testing — image quality of radiographs — experimental evaluation of image quality values and image quality tables.
DIN EN 462-5-94	Non-destructive testing; image quality of radiographs; image quality of indicators (duplex wire type); determination of total image unsharpness value.
DIN EN 473-93	Qualification and certification of NDT personnel; general principles.
DIN EN 571-1-92	Non-destructive testing; penetrant inspection; general principles for the examination.
DIN EN 571-3-95	Non-destructive testing — penetrant inspection — reference blocks.
DIN EN 583-1-92	Ultrasonic examination; general principles.
DIN EN 583-3-94	Non-destructive testing — ultrasonic examination — transmission technique.
DIN EN 584-1-94	Non-destructive testing — industrial radiographic film — classification of film systems for industrial radiography
DIN EN 584-2-94	Non-destructive testing — industrial radiographic film — control of film processing by means of reference values.
DIN EN 1289-94	Non-destructive examination of welds; penetrant testing of welds; acceptance levels and criteria
DIN EN 1290-94	Non-destructive examination of welds; magnetic particle testing of welds; method.
DIN EN 1291-94	Non-destructive examination of welds; magnetic particle testing of welds; acceptance levels and criteria.

DIN EN 1330-3-94 Non-destructive testing; terminology; terms used in industrial radiographic testing.

DIN EN 1330-4-95 Non-destructive testing — terminology — terms used in ultrasonic testing.

DIN EN 1330-6-94 Non-destructive testing — terminology — terms used in penetrant system.

DIN EN 1330-8-94 Non-destructive testing: terminology; terms used in testing for leak tightness.

DIN EN 1435-94 Non-destructive examination of welds; radiographic examination of welded joints.

DIN EN 1518-94 Non-destructive testing — leak testing — characterization of mass spectrometer leak detectors.

DIN EN 1593-94 Non-destructive testing — leak testing — bubble test method.

DIN EN 1711-95 Non-destructive examination of welds — eddy current examination by phase discrimination method.

DIN EN 1712-95 Non-destructive examination of welds — acceptance criteria for ultrasonic examination of welded joints.

DIN EN 1713-95 Non-destructive examination of welds — ultrasonic examination — characterization of imperfections in welds.

DIN EN 1714-95 Non-destructive testing of welds — ultrasonic ecamination of welded joints.

DIN EN 1779-95 Non-destructive testing — leak testing — guide to the method selection.

DIN EN 1956-95 Non-destructive testing — penetrant testing and magnetic particle testing — viewing conditions.

DIN EN 1968-95 Transportable gas cylinders — periodic inspection and testing of seamless steel gas cylinders excluding LPG).

DIN EN 4179-95 Aerospace series — qualification and approval of personnel for non-destructive testing.

DIN EN 10228-1-94 Non-destructive testing of steel forgings; magnetic particle inspection.

DIN EN 10228-2-94 Non-destructive testing of steel forgings; penetrant testing.

DIN EN 10228-3-95 Non-destructive testing of steel forgings — ultrasonic testing of ferritic or martensitic steel forgings.

DIN EN 10246-10-95 Non-destructive testing of steel tubes — radiographic testing of the weld seam of submerged arc-welded steel tubes for the detection of imperfections.

DIN EN 10246-15-95 Non-destructive testing of steel tubes — ultrasonic testing of strip/plate used in the manufacture of welded steel tubes for the detection of laminar imperfections.

DIN EN 12062-95 Non-destructive examination of welds — general rules.

DIN EN 12084-95 Non-destructive testing — eddy current examination — general principles and basic guidelines.

DIN EN 25580-92 Non-destructive testing; industrial radiographic illuminators; minimum requirements.

DIN ISO 2361-95 electrodeposited nickel coatings on magnetic and non-magnetic substrates — measurement of coating thickness — magnetic method.

DIN ISO 1114-3-95 Transportable gas cylinders — compatibility of cylinder and valve materials with gas contents — test methods.

AD HP 4-89 Test supervisors and testers in non-destructive testing.

AD HP 5/2-89 Manufacture and testing of joints; production testing of welds, testing of base metal after postweld heat treatment.

AD HP 5/3-89 Manufacture and testing of joints; non-destructive testing of welded joints

AD HP 5/3 Anlage 12 - 89 Non-destructive testing of welded joints; minimum requirement for non-destructive testing methods.

6.4.5 Japanese Industrial Standards Committee (JISC)

JIS G 0565-92 Methods for magnetic particle testing of ferromagnetic materials and classification of magnetic particle indications.

JIS G 0568-93 Method of eddy-current testing for steel products.

JIS G 0581-84 Methods of radiographic test and classification of radiographs for castings.

JIS G 0582-90 Ultrasonic examination for steel pipes and tubes

JIS G 0583-78 Eddy current examination of steel pipes and tubes

JIS G 0584-90 Ultrasonic examination for arc welded steel pipes

JIS G 0587-87	Methods for ultrasonic examination for carbon and low alloy steel forgings
JIS G 0801-93	Ultrasonic examination of steel plates for pressure vessels
JIS H 0502-86	Eddy current testing of copper and copper alloy pipes and tubes
JIS H 0515-92	Eddy current inspection of titanium pipes and tubes
JIS H 0516-92	Ultrasonic inspection of titanium pipes and tubes
JIS H 0521-68	Testing method for atmospheric corrosion of aluminium and aluminium alloys
JIS H 0522-69	Methods of radiographic test and classification of radiographs for aluminium castings
JIS H 0613-78	Visual inspection for sliced and lapped silicon wafers
JIS H 0614-78	Visual inspection for silicon wafers with specular surfaces
JIS W 0901-85	Aerospace fusion welders qualification
JIS W 0904-95	Liquid penetrant inspection for aerospace use
JIS W 0905-84	Aerospace non-destructive inspection personnel qualification and certification
JIS Z 2300-91	Glossary of terms used in non-destructive testing
JIS Z 2306-91	Radiographic image quality indicators for non-destructive testing
JIS Z 2314-91	Test methods for performance characteristics of eddy current testing instruments
JIS Z 2315-91	Test methods for performance characteristics of eddy current flaw detecting system
JIS Z 2319-91	Methods for magnetic leakage flux testing
JIS Z 2321-93	AC yoke magnet for magnetic particle testing
JIS Z 2329 91	Methods for buble leak testing
JIS Z 2330-92	Standard recommended guide for the selection of helium leak testing
JIS Z2331-92	Method for helium leak testing

JIS Z 2332-93	Test method for leaks using the pressure change measurement
JIS Z 2333-93	Test method for leaks using ammonia gas
JIS Z 2342-91	Methods for acoustic emission testing of pressure vessels during pressure test
JIS Z 2343-92	Method for liquid penetrant testing and classification of the indication
JIS Z 2344-93	General rule of ultrasonic testing of metals by pulse echo technique
JIS Z 2345-94	Standard test blocks for ultrasonic testing
JIS Z 2350-92	Method for measurement of performance characteristics of ultrasonic probes
JIS Z 2351-92	Method for assessing the electrical characteristics of ultrasonic testing instrument using pulse echo technique
JIS Z 2352-92	Method for assessing the overall performance characteristics of ultrasonic pulse echo testing instrument
JIS Z 2353-91	Methods for measurement of ultrasonic velocity in solids by pulse technique using reference test pieces
JIS Z 2354-92	Method for measurement of ultrasonic attenuation coefficient of solids by pulse echo technique
JIS Z 2355-94	Methods for measurement of thickness by ultrasonic pulse echo technique
JIS Z 2371-94	Methods of neutral salt spray testing
JIS Z 2381-87	Recommeded practice for weathering test
JIS Z 3050-95	Method of nondestructive examination of weld of pipeline
JIS Z 3060-94	Method for ultrasonic examination for welds of ferritic steel
JIS Z 3062-88	Methods of ultrasonic examination for gas pressure welds of reinforcing deformed bars
JIS Z 3080-95	Methods of ultrasonic angle beam examination for butt welds of aluminium plates
JIS Z 3081-94	Methods of ultrasonic angle beam examination for welds of aluminium pipes and tubes

JIS Z 3082-95	Methods of ultrasonic examination for T type welds of aluminium plates
JIS Z 3101-90	Testing method of maximum hardness in weld heat-affected zone
JIS Z 3104-95	Methods of radiographic examination for welded joints in steel
JIS Z 3105-93	Method of radiographic examination for fusion welded butt joints of aluminium plates
JIS Z 3106-71	Methods of radiographic test and classification of radiographs for stainless steel welds.
JIS Z 3107-93	Methods of radiographic examination for titanium welds by X-rays
JIS Z 3108-86	Methods of radiographic test for circumferential butt welds of aluminium pipes and tubes
JIS Z 3109-88	Method of radiographic testing for aluminium T-welds.
JIS Z 3111-86	Methods of tension and impact tests for deposited metal
JIS Z 3861-79	Standard qualification procedure for radiographic testing technique of welds
JIS Z 3871-87	Standard qualification procedure for ultrasonic testing technique of aluminium and aluminium alloy welds
JIS Z 4202-93	Geiger-muller counter tubes
JIS Z 4301-90	X-ray film badges
JIS Z 4302-90	Gamma-ray and hard X-ray film badges
JIS Z 4308-91	Direct reading personal dosemeters for X and gamma radiation
JIS Z 4312-90	Personal alarm dosemeters for X-rays and gamma-ray
JIS Z 4314-95	Radiophotoluminescent glass dosemeter systems
JIS Z 4323-91	Film badge for X-rays, gamma rays and thermal neutrons
JIS Z 4324-80	Area monitors for X and gamma rays
NDIS 2105-76	Evaluation of performance characteristics of portable pulse-echo ultrasonic thickness meter.
NDIS 2407-76	Methods for automatic ultrasonic testing of steel welds.

NDIS 2408-79	Measuring method of thickness by portable pulse-echo ultrasonic thickness meter.
NDIS 0601-77	Rule for certification of non-destructive testing personnel.

6.4.6 Standards Association of Australia (SAA)

AS NZS ISO 8402-94 Quality management and quality assurance — Vocabulary

AS Z5.2-68	Terminology of and abbreviations for fusion weld imperfections as revealed by radiography
AS 1101.3-87	Welding and non-destructive examination
AS 1065-88	Non-destructive testing — Ultrasonic testing of carbon and low alloy steel forgings
AS 1171-76	Methods for magnetic particle testing of ferromagnetic products and components
AS 1633-85	Acoustics-Glossary of terms and related symbols
AS 1710-86	Non-destructive testing of carbon and low alloy steel plate — Test methods and quality classification
AS 1796-93	Certification of welders and welding supervisors
AS 1929-81	Non-destructive testing — Glossary of terms
AS 2062-77	Methods for non-destructive penetrant testing of products and components
AS 2083-81	Calibration blocks and their methods of use in ultrasonic testing
AS 2084-87	Non-destructive testing — Eddy current testing of metal tubes
AS 2085-77	Magnetic particle testing media
AS 2177-	Non-destructive testing — Radiography of welded butt joints in metal
AS 2177.1-94	Methods of test
AS 2177.2-82	Image quality indicators (IQI) and recommendations for their use
AS 2207-94	Non-destructive testing — Ultrasonic testing of fusion welded joints in carbon and low alloy steel
AS 2331 (Set)	Methods of test for metallic and related coatings

AS 2331.1.4-82	Magnetic induction and eddy current methods
AS 2452	Non-destructive testing — Determination of thickness
AS 2452.1-82	Determination of the wall thickness of pipe by the use of radiography
AS 2452.2-81	Determination of the remaining wall thickness of corroded pipe by the use of radiography
AS 2452.3-85	Use of ultrasonic testing
AS 2565-82	Non-destructive testing — Penetrant testing media
AS2565-82	Non-destructive testing — Ultrasonic testing of steel castings and classification of quality
AS 2812-85	Welding, brazing and cutting of metals — Glossary of terms
AS 2824-85	Non-destructive testing — Ultrasonic methods — Evaluation and quality classification of metal bearing bonds
AS 3507-87	Non-destructive testing — Radiography of steel castings and classification of quality
AS 3669-89	Non-destructive testing — Qualification and registration of personnel — Aerospace
AS 3670-89	Non-destructive testing — Ultrasonic testing of universal beams and columns
AS 3788-90	Boilers and pressure vessels — In- service inspection
AS 3978-91	Non-destructive testing —Visual inspection of metal products and components
AS 3998-92	Non-destructive testing — Qualification and certification of personnel — General engineering
SAA HB34-92	Near-to-surface testing of hardened concrete

6.4.7 Standards Council of Canada

CAN CSA-Q9003-91	Quality systems — Quality assurance in final inspection and test
CGSB 48-GP-12M	Liquid penetrant inspection
CGSB 48-GP-13M	Certification of non-destructive testing personnel (eddy current method)

CGSB 48-GP-1M Recommended practices for magnetic particle inspection of commercial steel castings, forgings and weldments for surface and near-surface discontinuities

CGSB 48-GP-4M Certification of non-destructive testing personnel (industrial radiography method)

CGSB 48-G-5M Manual on industrial radiography

CGSB 48-GP-6a Recommended practices for ultrasonic inspection of structural welds

CGSB 48-GP-7M Certification of non-destructive testing personnel (industrial ultrasonic method)

CGSB 48-GP-8M Certification of non-destructive testing personnel (magnetic particle method)

CGSB 48-GP-9M Certification of non-destructive testing personnel (liquid penetrant method)

CGSB 48-GP-11M Manual on magnetic particle inspection

CGSB CAN/CGSB-48.16-92 Radiography inspection of aircraft structures

CGSB CAN/CGSB 48.2-92 Spot radiography of welded butt joints in ferrous materials

CGSB CAN/CGSB 48.3-92 Radiographic testing of steel castings

CGSB CAN/CGSB 48.7-93 Certification of non-destructive testing personnel (industrial ultrasonic method)

CSA CAN3-N285.4-M83 Periodic inspection of CANDU nuclear power plant components

CSA CAN3-N287.7-M80 In-service examination and testing requirements for concrete containment structures for CANDU nuclear power plants

CSA CAN/CSA-N28.5-M90 Periodic inspection of CANDU nuclear power plant containment components

CSA CAN/CSA-N285.6.6-88 Inspection criteria for zirconium alloys

CSA CAN/CSA-N286.0-92 Overall quality assurance programme requirements for nuclear power plants

CSA CAN/CSA-N286.4-M86 Commissioning quality assurance for nuclear power plants

CSA N287.5-93 Examination and testing requirements for concrete containment structures for CANDU nuclear power plants

CGSB CAN/CGSB-48.16-92 Radiographic inspection of aircraft structures

6.4.8 American Society for Testing and Materials (ASTM)

A 275/A275M-94 Test method for magnetic particle examination of steel forgings

A388/A388M-94 Practice for ultrasonic examination of heavy steel forgings

A 418-94 Test method for ultrasonic examination of turbine and generator steel rotor forgings

A 435/A435M-90 Specification for straight-beam ultrasonic examination of steel plates

A456-94 Specification for magnetic particle examination of large crankshaft forgings

A 503-75 (94) Specification for ultrasonic examination of large forged crankshafts

A 531/A531M-91 Practice for ultrasonic inspection of turbine-generator steel retaining rings

A 880-89 (94) Practice for criteria for use in evaluation of testing laboratories and organizations for examination and inspection of steel, stainless steel, and related alloys

A 898/A898M-91 Specification for straight beam ultrasonic examination of rolled steel structural shapes

A 903/A903M-91 Specification for steel castings, surface acceptance standards, magnetic particle and liquid penetrant inspection

B 244-79 (93) Test method for measurement of thickness of anodic coatings on aluminium and of other non-conductive coatings on non-magnetic basis metals with eddy-current instruments

B 499-88 Test method for measurement of coasting thicknesses by the magnetic method: non-magnetic coatings on magnetic basis metals

B 530-88 Method for measurement of coating thicknesses by the magnetic method: electrodeposited nickel coatings on magnetic and non-magnetic substrates

B 548-90	Method for ultrasonic inspection of aluminium-alloy plate for pressure vessels
B 659-90	Guide for measuring thickness of metallic and inorganic coatings
B 681-88 (94)	Method for measurement of thickness of anodic coatings on aluminium and of other transparent coatings on opaque surfaces with the light — section microscope
B 773-87 (91)	Guide for ultrasonic C-scan bond evaluation of brazed or welded electrical contact Assemblies
C 1133-89	Test method for non-destructive assay of special nuclear materials in low density scrap and waste by segmented passive gamma scanning
C 1175-93	Guide to test methods and standards for non-destructive testing of advanced ceramics
D 1186-93	Test methods for non-destructive measurement of dry film thickness of non-conductive coatings applied to a non-ferrous base
D 1400-94	Test method for non-destructive measurement of dry film thickness of non-conductive coatings applied to a non-ferrous metal base
D2845-90	Test method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock
D 4991-94	Test method for leakage testing of empty rigid containers by vacuum method
E 94-93	Guide for radiographic testing
E 213-93	Practice for ultrasonic examination of metal pipe and tubing
E 214-68 (91)	Practice for immersed ultrasonic examination by the reflection method using pulsed longitudinal waves
E 215-87 (92)	Practice for standardising equipment for electromagnetic examination of seamless aluminium-alloy tube
E 242-91	Reference radiographs for appearances of radiographic images as certain parameters are changed
E 243-90	Practice for electromagnetic (eddy-current) examination of copper and copper-alloy tubes
E 272-91	Reference radiographs for high-strength copper-base and nickel-copper alloy castings

E 273-93	Practice for ultrasonic examination of longitudinal welded pipe and tubing
E 280-93	Reference radiographs for heavy-walled (41/2 to 12-in (114 to 305-mm) steel castings
E309-93a	Practice for eddy-current examination of steel tubular products using magnetic saturation
E 310-94	Reference radiographs for tin bronze castings
E 376-89 (94)	Practice for measuring coating thickness by magnetic-field or eddy-current (electromagnetic) test methods
E 390-91a	Reference radiographs for steel fusion welds
E 426-92	Practice for electromagnetic (eddy-current) examination of seamless and welded tubular products, austenitic stainless steel and similar alloys
E 427-94	Practice for testing for leaks using the halogen leak detector (alkali-ion diode)
E428-92	Practice for fabrication and control of steel reference blocks used in ultrasonic inspection
E 431-92	Guide to interpretation of radiographs of semiconductors and related devices
E 432-91	Guide for selection of a leak testing method
E 433-71 (93)	Reference photographs for liquid penetrant inspection
E 446-93	Reference radiographs for steel castings up to 2 in. (51 mm) in thickness
E 453-79 (90)	Practice for examination of fuel element cladding including the determination of the mechanical properties
E 479-91	Guide for preparation of a leak testing specification
E 493-94	Test methods for leaks using the mass spectrometer leak detector in the inside-out testing mode
E 494-95	Practice for measuring ultrasonic velocity in materials
E 498-95	Test methods for leaks using the mass spectrometer leak detector or residual gas analyser in the tracer probe mode

E 499-94	Test methods for leaks using the mass spectrometer leak detector in the detector probe mode
E 505-91	Reference radiographs for inspection of aluminium and magnesium die castings
E 515-94	Test method for leaks using bubble emission techniques
E 543-95	Practice for evaluating agencies that perform non-destructive testing
E 545-91	Method for determining image quality in direct thermal neutron radiographic examination
E 566-94	Practice for electromagnetic (eddy-current) sorting of ferrous metals
E 569-85 (91)	Practice for acoustic emission monitoring of structures during controlled stimulation
E 570-91	Practice for flux leakage examination of ferromagnetic steel tubular products
E 571-92	Practice for electromagnetic (eddy-current) examination of nickel and nickel alloy tubular products
E 587-94	Practice for ultrasonic angle-beam examination by the contact method
E 588-88	Practice for detection of large inclusions in bearing quality steel by the ultrasonic method
E 592-94	Guide to obtainable ASTM equivalent penetrameter sensitivity for radiography of steel plates 1/4 to 2 in. (6 to 51 mm) thick with x rays and 1 to 6 in. (25 to 152 mm) thick with cobalt-60
E 647-95	Test method for measurement of fatigue crack growth rates
E 664-93	Practice for the measurement of the apparent attenuation of longitudinal ultrasonic waves by immersion method
E 665-94	Practice for determining absorbed dose versus depth in materials exposed to the x-ray output of flash x-ray machines
E 689-95	Reference radiographs for ductile iron castings
E 690-91	Practice for in-situ electromagnetic (eddy-current) examination of non magnetic heat exchanger tubes
E 703-79 (92)	Practice for electromagnetic (eddy-current) sorting of non-ferrous metals

E 709-95	Guide for magnetic particle examination
E 746-93	Test method for determining relative image quality response of industrial radiographic films
E 748-90	Practices for thermal neutron radiography of materials
E 749-80 (91)	Practice for acoustic emission monitoring during continuous welding
E 750-88 (93)	Practice for characterising acoustic emission instrumentation
E 751-80 (91)	Practice for acoustic emission monitoring during resistance spot-welding
E 797-94	Practice for measuring thickness by manual ultrasonic pulse-echo contact method
E 801-91	Practice for controlling quality of radiological examination of electronic devices
E 802-91	Reference radiographs for grey iron castings up to 4 1/2 in (114 mm in thickness
E 803-91	Method for determining the L/D radio of neutron radiography beams
E 908-91	Practice for calibrating gaseous reference leaks
E 976-94	Guide for determining the reproducibility of acoustic emission sensor response
E 994-95	Guide for calibration and testing laboratory accreditation systems general requirements for operation and recognition
E 999-95	Guide for controlling the quality of industrial radiographic film processing
E 1000-92	Guide for radioscopy
E 1001-90	Practice for detection and evaluation of discontinuities by the immersed pulse-echo ultrasonic method using longitudinal waves
E 1002-94	Test method for leaks using ultrasonics
E 1003-94	Test method for hydrostatic leak testing
E 1004-91	Test method for electromagnetic (eddy-current) measurements of electrical conductivity

E 1005-84 (91)	Test method for application and analysis of radiometric monitors for reactor vessel surveillance
E 1025-94	Practice for design, manufacture, and material grouping classification of hole-type image quality indicators (IQI) used for radiology
E 1030-91	Test method for radiographic examination of metallic castings
E 1032-92	Method for radiographic examination of weldments
E 1033-91	Practice for electromagnetic (eddy-current) examination of type F-continuously welded (CW) ferromagnetic pipe and tubing above the curie temperature
E 1065-92	Guide for evaluating characteristics of ultrasonic search units
E 1066-94	Test method for ammonia colorimetric leak testing
E 1067-89 (91)	Practice for acoustic emission examination of fibreglass reinforced plastic resin (FRP) tanks/vessels
E 1079-85 (91)	Practice for calibration of transmission densitometers
E 1106-86 (92)	Method for primary calibration of acoustic emission sensors
E 1114-92	Test method for determining the focal size of iridium-192 industrial radiographic sources,
E 1118-95	Practice for acoustic emission examination of reinforced thermosetting resin pipe (RTRP)
E 1139-92	Practice for continuous monitoring of acoustic emission from metal pressure boundaries
E 1158-90 (94)	Guide for materials selection and fabrication of reference blocks for the pulsed longitudinal wave ultrasonic examination of metal and metal alloy production material
E 1161-91	Test method for radiological testing of semiconductors and electronic components
E1187-90	Terminology relating to laboratory accreditation
E 1208-94	Test method for fluorescent liquid penetrant examination using the lipophilic post-emulsification process
E 1209-94	Test method for fluorescent liquid penetrant examination using the water-washable process

E 1210-94	Test method for fluorescent liquid penetrant examination using the hydrophilic post-emulsification process
E 1211-87 (92)	Practice for leak detection and location using surface-mounted acoustic emission sensors
E 1212-95	Practice for establishment and maintenance of quality control systems for non-destructive testing agencies
E 1219 -94	Test method for fluorescent liquid penetrant examination using the solvent removable process
E 1220-92	Test method for visible penetrant examination using the solvent removable process
E 1254-92	Guide for storage of radiographs and unexposed industrial radiographic films
E 1255-92b	Practice for radioscopy
E 1301-89	Guide for development and operation of laboratory proficiency testing programs
E 1312-94	Practice for electromagnetic (eddy-current) examination of ferromagnetic cylindrical bar product above the curie temperature
E 1315-93	Practice for ultrasonic examination of steel with convex cylindrically curved entry surfaces
E 1316-95a	Terminology for non-destructive examinations
E 1320-91	Reference radiographs for titanium castings
E 1322-90	Guide for selection, training and evaluation of assessors for laboratory accreditation systems
E 1324-92	Guide for measuring some electronic characteristics of ultrasonic examination instruments
E 1359-92 (95)	Guide for surveying non-destructive testing agencies
E 1390-90 (95)	Guide for illuminators used for viewing industrial radiographs
E 1411-91	Practice for qualification of radioscopic systems
E 1416-92	Test method for radioscopic examination of weldments
E 1417-95a	Practice for liquid penetrant examination

E 1418-92	Test method for visible penetrant examination using the water-washable process
E 1419-91	Test method for examination of seamless, gas-filled, pressure vessels using acoustic emission
E 1441-95	Guide for computer tomography (CT) imaging
E 1444-94a	Practice for magnetic particle examination
E1453-93	Guide for storage of media that contains analog or digital radioscopic data
E 1454-92	Guide for data fields for computerized transfer of digital ultrasonic testing data
E 1475-92	Guide for data fields for computerized transfer of digital radiological test data
E 1495-92	Guide for acousto-ultrasonic assessment of composites, laminates, and bonded joints.
E 1496-92	Test method for neutron radiographic dimensional measurements
E 1570-95	Practice for computer tomographic (CT) examination
E 1571-94	Practice for electromagnetic examination of ferromagnetic steel wire rope
E 1580-93	Guide for surveillance of accredited laboratories
E 1603-94	Test methods for leakage measurement using the mass spectrometer leak detector or residual gas analyser in the hood mode
E 1606-94	Practice for electromagnetic (eddy-current) examination of copper redraw rod for electrical purposes
E 1645-95	Reference radiographs for examination of aluminium fusion welds
E 1672-95	Guide to computer tomography (CT) system selection
E 1685-95	Practice for measuring the change in length of fasteners using the ultrasonic pulse-echo technique
E 1695-95	Test method for measurement of computed tomography (CT) system performance
F 78-79 (91)	Test method for calibration of helium leak detectors by use of secondary standards.

F 134-85 (90)	Test methods for determining hermeticity of electron devices with a helium mass spectrometer leak detector
F 601-92	Practice for fluorescent penetrant inspection of metallic surgical implants
F 1052-87 (91)	Practice for pressure testing of gas-tight, totally encapsulating
G 12-83 (92)	Test method for non-destructive measurement of film thickness of pipeline coatings on steel
G 15-93	Terminology relating to corrosion and corrosion testing.

Note: In addition to the ASTM standards listed above, there are numerous others which have been developed by ASTM committees other than committee E-7 on NDT. For detailed list of such standards the index to the ASTM Annual Book of Standards can be consulted.

6.4.9 The American Society of Mechanical Engineers (ASME)

ASME Boiler and Pressure Vessel Code consists of the following sections:

Section I	Power boilers.
Section II	Materials specifications.
Section III	Rules for construction of nuclear power plant components.
Section IV	Heating boilers.
Section V	Non-destructive Examination (1995). This section contains a total of 22 articles. Article 1 is introductory and covers general requirements such as manufacturer's examination responsibility, duties of the authorized inspector, written procedures, inspection and examination and qualification of personnel. The balance of Section V is organized into two subsections, A and B along with two appendices and an Index. Appendix A contains a glossary of terms and Appendix B the SI Units. Subsection A (Articles 2 to 13) defines the specific NDE methods required by the ASME code. Subsection B (Articles 22 to 30) contains the basic standards, procedures, and recommended practice documents for each of the NDE techniques as adopted from the American Society for Testing and Materials (ASTM). For example ASTM E 94 becomes SE-94 and ASTM A 609 becomes SA-609.
Section VI	Recommended rules for care and operation of heating boilers.
Section VII	Recommended rules for care and operation of power boilers.
Section VIII	Pressure vessels.

Section IX	Welding and brazing qualifications.
Section X	Fibreglass — reinforced plastic (FRP) pressure vessels.
Section XI	Rules for in-service inspection of nuclear power plant components.

6.4.10 Other standardization bodies

Besides the standardization bodies mentioned before there are other standardization bodies as well from various countries such as Austria, Belgium, Denmark, France, Italy, Netherlands, Norway, Spain, Sweden and Switzerland.

In addition to Australia and Japan, almost all the RCA member states in the region have organizations for standards. In most cases, however, their standards are adopted from the standards of one or more of the international organizations for standardization.

7. EVALUATION OF TEST RESULTS

7.1 SIGNIFICANCE OF DEFECTS AND NEED FOR PROPER EVALUATION OF NDT RESULTS

It is a fact that there are inherent flaws in materials due to crystal lattice imperfections and dislocations howsoever microscopic they may be in size. Further flaws may come from the manufacturing processes such as welding, casting, forging and surface treatment, etc. (Section 2.3). The materials have to perform under various conditions of stress, fatigue and corrosion, etc. Because of these conditions additional defects may be created or those already present may be aggravated. It has also been established by now that most material failures take place due to these defects reaching dangerous sizes such that the remaining parts of materials cannot withstand the stresses to which they are subjected and therefore fail in a ductile or brittle manner.

There is therefore, a need firstly to detect these flaws and secondly to evaluate them in terms of their nature, size and location. A further step should be to assess as to how severe and dangerous these flaws are in their present state and whether they need to be removed by repairing the tested component or whether the component is to be scrapped or can the product with these known flaws still be allowed to go into service? This process of judgement and decision is termed as "evaluation" and is, in fact, replacing the concept of non-destructive testing (NDT) by non-destructive evaluation (NDE).

Evaluation should really mean two things: first to make sure that no components with unacceptable level of defects are able to escape inspection and go into service because this, as has been said earlier at numerous places, can lead to catastrophic failures; second, it is equally important that components known to have such defects which are not considered to be dangerous for the particular service are not stopped from going into service as this can mean colossal production and material losses. Accordingly there are two basic requirements, firstly to find reliably and

accurately the defects in terms of their nature, size and location and secondly to make judgement and decision on their further treatment. The first requirement is met by utilizing appropriate NDT methods for detection and determination of nature, size and location of defects while for the second the judgement of suitability or fitness for purpose is exercised with the help of acceptance standards. The judgement is also made by following a more rigorous fracture mechanics approach wherein the size of the flaw specially a crack is studied under various load conditions and its behaviour response predicted through calculations.

7.2 DETERMINATION OF FLAW CHARACTERISTICS IN NDT

We may start with explaining the concept of flaw detection sensitivity in NDT. This is simply the ability or capability of an NDT technique to detect flaws. If a particular technique can detect minute defects it is said to have a good or high sensitivity while on the other hand if it can only detect gross or larger defects it is said to have a poor or low sensitivity.

It is important that the sensitivity of flaw detection chosen is compatible with the requirements of inspection. This means that if, for example, it is required to be able to detect internal flaws of 1 mm size in a particular fabrication then the technique of radiographic or ultrasonic testing should be such that it would be able to detect this size of flaws under normal circumstances with reliability and reproducibility. We shall discuss these aspects in case of individual NDT methods in the following sections. While there are control factors which are typical of these individual NDT methods there are other parameters which are common to all methods. These include marking of the test specimen and its specific area being inspected in a particular test with a unique identification number. This number is cross referred to the inspection report of the specimen and helps in rectification of the defect if desired or in its periodic monitoring. The objects needing inspection should be segregated and partitioned. This will help in ensuring the certainty and correctness of the test results which are pre-requisite for their reliability. The inspector must know the background of the specimen, its manufacturing history and material. This combined with a knowledge of the technique of testing can help in proper interpretation of test indications.

7.2.1 Liquid penetrant testing

In liquid penetrant testing the factors that influence the sensitivity of detection have been listed in Section 6.1.1 and an explanation of most of these is provided in Section 7.2. These will be briefly mentioned again in relevance to assessing the ability of liquid penetrant testing methods for the characterization of flaws. These factors are: the type of specimen, its geometry and surface condition; the nature, type, location and size of the defects being looked for; colour, volatility and viscosity of penetrants; method of application of penetrants and the dwell or the residence time allowed; method of cleaning both before and after the application of penetrant; type of developer, its fineness of grain size and its mobility and the contrast it provides with the penetrant used; black light and the general lighting conditions and lastly the operator's eye sight, qualifications and experience. A

careful control over these parameters is needed to have the desired sensitivity as well as for the results to be reliable and reproducible.

Sensitivity of penetrant process is defined rather vaguely in most of the standards in terms of "normal", "high" or "ultrahigh", etc. However, for any given penetrant system, its sensitivity or flaw size detection capability will depend on (a) the amount of penetrant that gets into the crack, (b) the amount of penetrant that remains within the crack after the surface removal step, (c) the amount of penetrant that comes back out of the crack during the developing process, (d) the visibility of the indication, and (e) the "signal to noise ratio" of indication to background interference. Sensitivity is measured by using heat cracked aluminium blocks, fine wire tightly wound on a precision mandrel, cracked nickel-chromium panels and crazed anodized coatings having cracks of known widths and depths induced into the plating. These sensitivity panels can be used over and over again. It is possible to compare one penetrant system to another sequentially by first using one type of penetrant and then the second on identical blocks and comparing the results.

There are also test panels with surface indentations simulating flaws and for measurement of background levels which act as an aid in comparison and evaluation of penetrant systems. Practically all modern inspection penetrants are capable of penetration into the finest cracks down to a few micrometres. However, the human eye is not capable of differentiating a flaw indication of 2 μm width and a 4 μm width and such indications have to be seen under a microscope.

Having established that the sensitivity of the penetrant system chosen is adequate for detection of flaws of desired dimensions and having completed the process of liquid penetrant testing, the next step is to view the indications from the test under appropriate lighting conditions and to interpret and evaluate them. Firstly it is to be remembered that liquid penetrant testing is limited to detection of defects which have an opening to the surface. Some points regarding the typical indications of different types of surface defects are given in Section 3.2.1. Here we will concentrate on their evaluation.

The presence of an indication needs to be related to the type of defect, the size of defect and the location of the defect causing that indication. The location is directly marked by the indication on the surface of the test specimen. Quantitative information on the type and size of defect is not always obtainable from surface inspection alone. Penetrant indications do, however, provide the experienced with qualitative data on which to base a decision. The type and size of the flaw must be known to evaluate what effect will this flaw have on the anticipated service of the part.

In case of fluorescent penetrants the intensity of fluorescence is associated with the concentration of penetrant retained in the flaw. If dye penetrant is used, then its richness of colour on the surface is closely related to the volume of the entrapped penetrant and, therefore, to the size of the discontinuity. It is difficult for the human eye to detect slight differences in colour of dye or brilliance of fluorescence. Tests show that although instruments can record 4% differences in brightness, the eye cannot see less than 10% difference. It is fortunate that larger flaws nearly always produce larger indications in addition to the increased

brightness. The cracks show linear indications whose width and brightness of fluorescence or colour depend on the volume of the crack. Cold shuts in castings and forging laps may also cause continuous line type indications. Intermittent line type images may be caused by forging laps which are partially welded due to blows of forging hammer or due to cracks which do not reach the surface for their entire length. Rounded indications may signify pin holes or blowholes or may also be due to deep crater cracks in welds. The sharpness of penetrant indications is affected by the volume of the liquid retained in the discontinuity, the test conditions such as temperature and time allowed for the indications to develop and the type of penetrant used. Generally clear-cut indications come from narrow linear discontinuities. Another parameter to evaluate the indications of penetrants is the time required for an indication to develop. This is inversely proportional to the volume of the discontinuity. The larger the defect, the more quickly will the penetrant entrapped therein be pulled out by the developer. It is important to allow sufficient time for the appearance of minute indications from fine defects. In order to use time for indication to develop as a measure of the extent of the flaw, the other variables such as type of penetrant, sensitivity of technique, temperature of part, residence times and conditions of examination must be controlled.

One good way to estimate the size of defect is by the persistence of the indication. If it reappears after the developer has been removed and reapplied, there must be a reservoir of penetrant present. In case of faint or weak indications where there is some doubt as to the type or even the existence of a flaw, it is good practice to repeat the entire penetrant inspection. If the indication reappears, it is probably due to a small flaw rather than to incomplete cleaning.

7.2.2 Magnetic particle testing

For magnetic particle testing, as already mentioned in Section 6.1.1, the test sensitivity depends upon the type of specimen, the test sensitivity depends upon the type of the specimen, its geometry and shape and surface condition; the nature, type, location and size of the defects being looked for; the method and level of magnetization; properties of contrast agents; colour, size and viscosity of magnetic particles; viewing conditions and lighting arrangements and the operator's eye sight, qualifications, skill and experience.

Reference standards may be used to evaluate the functionality or performance of a magnetic particle testing system. Two kinds of artificial discontinuities are used for magnetic particle test system: (1) those designed to indicate the adequacy of the field in an unknown test object; and (2) those designed to measure the effectiveness of the testing system independent of the test object. There are a number of reference blocks in use. First one is the tool steel ring standard which is commonly used and universally recognized reference standard for magnetic particle testing systems. It consists of a tool steel ring having 1.78 mm diameter holes at varying distances from the edge, and the sensitivity is determined from the number of holes made visible by a certain system as related to the level of magnetization- larger the number of holes, higher the sensitivity. The prism block is another reference standard containing an artificial discontinuity. Truncated half-prisms are built with one face at an angle and when two such components are bolted together, an artificial crack is formed. The sloped surface of the block can

be positioned at variable distances from the conductor. When current is passed through the conductor, the leakage field from the crack gradually weakens along the prism face. A specified amperage is applied through the conductor and the length of the magnetic particle indication is used to measure the test sensitivity. Another version of the block standard consists of two ground steel blocks forming an artificial crack at their contact surfaces, similar to the discontinuity formation in the split prism test block. On one of face ends, a small permanent magnet is fixed below a brass cover causing magnetic flux leakage from the artificial discontinuity. This leakage field decreases with greater distance from the magnet, so that longer discontinuity indications reveal higher test sensitivity. Additional standard test blocks which help in qualitatively establishing the sensitivity of magnetic particle testing systems include scribed ferromagnetic shims and magnetic paste-on tapes. Gauss meters based on "Hall effect" and flux density meters are also used to measure the magnetic field strength at various locations in the vicinity of the test object thereby helping in establishing repeatable test procedures for magnetic particle testing.

In applications such as aerospace or plant maintenance, magnetic tests need to be very sensitive. Extremely small discontinuities must be detected and correspondingly small test indications must be produced for evaluation and interpretation. For some applications, high sensitivity is actually a problem since excess leakage fields produce false indications and dense backgrounds. The magnetic particle test sensitivity must be established in order to indicate discontinuities within a range of severity appropriate to the application.

Unlike other non-destructive testing methods, magnetic particle testing systems give little evidence of malfunction. The absence of a test indication could mean that (1) tests were properly performed on samples without discontinuities; or (2) the testing system was not working and therefore not locating existing discontinuities. As a result, some form of reference standard is needed to determine proper system performance and adequate sensitivity. Such a system evaluation tool should check for concentration of the magnetic particle bath, material visibility (loss of fluorescence on fluorescent oxides), particle concentration (for wet methods), adequate particle mobility, and the ability to generate an appropriate magnetic field. When multiple variables can affect the outcome of a test, a means should be used to normalize or standardize the test. This ensures that consistent, repeatable results are achieved, independent of the machine, the operator or the time of the test. The most direct way to achieve consistent results is to regularly use a reference standard such as a prism block to compare system sensitivity to pre-established tolerances. If the desired sensitivity is not achieved, testing should be stopped to allow required system adjustments.

In Section 3.3 some hints about evaluation of magnetic particle testing indications have already been given. These will be supplemented in this section. It is suggested that the typical appearances of indications from flaws be read in conjunction with Sections 3.3 and 3.4 where the causes of occurrence of these flaws have been described. Simultaneously it is important to know that surface-breaking discontinuities best detected by magnetic particle tests are those that expel the optimal magnetic flux leakage for the technique. In order to gain a clearer insight of this, it is necessary to understand three sets of variables; first how the

discontinuity parameters affect the external flux leakage, second, how magnetic field parameters affect the external flux leakage field and third, how the sensor reacts to passing through such fields.

The discontinuity characteristics that are critical to the formation of magnetic particle indications include depth, width, and angle to the object surface. In cases where the discontinuity is narrow and surface breaking (seams, laps, quench cracks and grind tears), the magnetic flux leakage field near the mouth of the discontinuity is highly curved. The activating field strength may be quite small (a few amperes per metre) or, after saturating the test object, inspection can be performed with the resulting residual induction. In the case of subsurface discontinuities (inclusions and laminations), the magnetic flux leakage field at the inspected surface is much less curved. Relatively high values of field strength and flux density within the object are required for testing. This lack of leakage field curvature greatly reduces the particles ability to stick to such indications.

Typical flaw size that can be determined using the wet method of magnetic particle testing could be cracks of widths 0.25 to 2.3 mm. Discontinuities less than about 0.37 mm deep may be called fine cracks while those having greater depths may be termed as coarse cracks.

A cold shut is initiated during the metal casting process. It occurs because of imperfect fusion between two streams of metal that have converged. Cold shuts may also be attributed to surging, sluggish molten metal, an interruption in pouring or any factor that prevents fusion where two molten surfaces meet. This discontinuity produces magnetic particle indications similar to those of cracks or seams with smooth or rounded edges.

Hot tears appear on the surface as a ragged line of variable width and numerous branches. In some instances the cracks are not detectable until after machining because tearing can be subsurface.

Laminations can be detected by magnetic particle testing at an end or a transverse cross section taken through the rolled plate.

Lack of fusion may or may not occur near the outside surface of the weld joint. The closer it is to the surface, the sharper the magnetic particle indication. Lack of fusion is usually oriented parallel to the direction of welding and the test indication often appears at or near the toe of the weld.

The magnetic particle indication produced by lack of penetration has an appearance similar to a subsurface longitudinal crack and usually follows the centreline of the weld.

A magnetic particle indication of subsurface porosity is typically weak and not clearly defined. All but the smallest surface pores should be visible to the unaided eye.

A magnetic particle indication produced by a slag inclusion is weak and poorly defined and high magnetizing field strength is required for detection. Tungsten inclusions are found in the weld metal deposited by the gas tungsten arc welding

(GTAW) process and are usually the result of allowing the molten weld pool or the filler metal to come in contact with the tip of the tungsten electrode. This type of inclusion is virtually undetectable by magnetic particle methods.

7.2.3 Eddy current testing

The diversified applications and range and limitations of eddy current testing have been described in Section 3.4. The test sensitivity for eddy current testing is dependent upon many variable factors important among which are the type of specimen, its geometry, shape, surface condition, conductivity and composition; nature, location and size of defects; characteristics such as frequency, impedance and diameter of the probe; type of equipment; the quality and precision of known-defect specimens used for calibration and the qualifications, skill and experience of the operator. An important aspect is the limited depth of penetration of eddy currents into the test specimen as the eddy currents is basically a surface phenomenon and shows skin effect. The standard depth of penetration is given by $\delta = 1/(\pi f \mu_0 \mu \sigma)$ where all quantities have meanings as given in Section 3.4. This shows that the skin depth depends on conductivity, permeability and frequency, but is relatively small for most metals (about 0.2 mm or 0.008 in. for copper at 100 kHz). This has two important effects on the design of eddy current probes: (1) the transducers are more useful for surface testing and (2) for subsurface testing, lower frequencies may be necessary in addition to special methods of increasing skin depth (such as magnetic saturation).

Eddy current testing is basically a comparison method. The system is calibrated and its sensitivity established with the help of standard test specimens of known specifications of composition, dimensions, conductivity and permeability, etc. and having flaws of precisely known dimensions. These flaws are usually precisely machined thickness, electro-discharge machined (EDM) notches, machined and natural cracks and drilled holes of precise diameters. Looking at the variety of inspection problems tackled by eddy current testing it is natural to expect that there is correspondingly a large variety of standard test specimens for the purpose of calibration and sensitivity setting. For example there are standards for tubing for heat exchangers and nuclear reactors, heat treated parts, bolt hole, coated substrates and thickness, conductivity, resistivity, hardness, steel rods and other specimens, thickness and thinning standards, seamless and welded pipes of steel, titanium, copper and aluminium and their alloys. An example of a discontinuity standard showing through-hole and electro machined notches for cladding tubing is shown in Table 7.1.

In almost all these cases the sensitivity is established by adjusting the equipment, specially the probe frequency, such that a standard and repeatable pattern on the oscilloscope screen is obtained from the known flaws in standard test blocks or tubes. For example in the case of the tubing, sensitivity is established by adjusting the frequency to achieve eddy current penetration equal to one cladding wall thickness or less. Phase control adjustments are made during standard calibration between OD, ID or through-wall response on the CRT screen and strip chart recorders. Best sensitivity is indicated by the 0.23 mm diameter through-hole. Screen appearances for different types of eddy current equipment for sensitivity calibration have already been explained in Section 3.4.1.

Signal amplitudes and phase angle changes due to flaws can be measured with high precision and analysed and related to flaw characteristics. The signals can also be readily digitized for display or record. Critical factors in selection of optimum crack test conditions include the eddy current density (A/cm^2) actually induced within the tube wall and the variation in eddy current phase angle between the inside diameter and the outside diameter of the tube. It is not sufficient to assume that if the exciting AC magnetizing field penetrates through the tube wall that the necessary eddy current magnitudes and phase conditions will be optimum for detection of both inside surface and outside surface cracks in non-magnetic tubes. In encircling coil tests of tubes for cracks, it is necessary that the cracks or other discontinuities interrupt or distort the eddy current flow paths and change the magnetic reaction field of the eddy currents to provide a recognisable signal. The ratio of the test sensitivity for detection of an inside surface discontinuity to that of an outside surface discontinuity corresponds to the ratio of the eddy current density at the inner surface to that at the outer surface of the tube.

TABLE 7.1 : DISCONTINUITY STANDARD SHOWING THROUGH-HOLE AND ELECTROMACHINED NOTCHES FOR CLADDING TUBING.

No.	Length	Width	Depth	Location	Type
1	3.25 mm (0.128 in.)	0.051 mm (0.002 in.)	0.064 mm (0.0025 in.)	ID	Transverse
2	0.23 mm (0.009 in.)	-	-	-	-
3	3.25 mm (0.128 in.)	0.074 mm (0.0029 in.)	0.241 mm (0.0095 in.)	OD	Longitudinal
4	3.25 mm (0.128 in.)	0.089 mm (0.0035 in.)	0.228 mm (0.0090 in.)	OD	Transverse
5	3.20 mm (0.126 in.)	0.064 mm (0.0025 in.)	0.078 mm (0.0031 in.)	OD	Longitudinal
6	3.23 mm (0.127 in.)	0.068 mm (0.0027 in.)	0.084 mm (0.0033 in.)	OD	Transverse
7	3.25 mm (0.128 in.)	0.076 mm (0.0030 in.)	0.231 mm (0.0091 in.)	ID	Longitudinal
8	3.25 mm (0.128 in.)	0.089 mm (0.0035 in.)	0.221 mm (0.0087 in.)	ID	Transverse
9	3.23 mm (0.127 in.)	0.064 mm (0.0025 in.)	0.084 mm (0.0033 in.)	ID	Longitudinal
10	3.23 mm (0.127 in.)	0.056 mm (0.0022 in.)	0.068 mm (0.0027 in.)	ID	Transverse

Bar sorting and testing is done with the help of encircling coils and uses the principle where the voltage induced in the secondary coil can be analysed utilizing the concepts of characteristic or limit frequency and the effective permeability. Also the similarity law may be applied according to which the effective permeability, as well as the geometrical distributions of the magnetic filed strength and eddy current densities, are the same for two different test objects if the frequency ratio f/f_g is the same for each test object. Using a comparison coil method wherein there are two coils one of which contains a crack-free bar with a known fill factor while the other coil is empty, the crack depths can either be quantitatively calculated using equations and charts specially developed by Institut Dr. Förster or can be computed from the calibrated instrument indications. The latter procedure involves the following steps:

1. Read the instrument's signal deflection height. For example, a crack of unknown depth might be indicated by a signal deflection amplitude A = 2.5 cm, when the instrument sensitivity control is set at N = 1 per cent per centimetre, and $f/f_g = 15$.

2. Multiply the signal deflection A by the sensitivity setting N to obtain the ratio Q. In this example, Q = N × A = (1 per cent per centimetre) × (2.5 per cent of the absolute value) = 2.5 per cent.

3. Using the curves, find the intersection of the ordinate for (Q = 2.5 per cent) with the crack depth curve for f/fg = 15. Read the corresponding crack depth on the abscissa scale.

Crack voltages as above for non-magnetic bars must be multiplied by the relative magnetic permeability of the ferromagnetic material to obtain the higher voltage magnitudes from cracks in ferromagnetic bars at a specific frequency ratio. Low frequency ratios provide the best crack depth sensitivity for ferromagnetic test bars. However, it is also possible to use magnetic saturation techniques to reduce the relative permeability of steels and other highly ferromagnetic materials to values near one. When this is done, the procedures given for crack tests of non-magnetic bars can be applied to ferromagnetic bars, with good approximation to actual test indications.

An important application of eddy current tests is in non-contact measurements of the thickness, electrical conductivity and magnetic permeability of flat metallic sheets, foils and surface films. Such tests permit rapid thickness gauging, alloy separation, detection of wall thinning by corrosion or wear, control of heat treating operations or measurement of damage to metallic materials. Test coils or probes can often be made with small dimensions, for easy manual positioning and for access to various areas of parts formed from sheet materials.

Detection of discontinuities in sheet materials is limited to cases in which discontinuities have a component perpendicular to the direction of eddy current flow paths. In general, laminations and separations between parallel layers in sheet materials cannot be detected reliably by eddy current tests because the induced eddy current flow is typically parallel to the sheet surface through which excitation is applied.

Spherical and cylindrical parts may be tested using circular test coils. Also the wall thickness and wall thinning, etc. in ferromagnetic pipes can be measured. In such pipes pits and cracks can also be detected by passing a single and relatively simple probe through them.

7.2.4 Radiographic testing

The factors that affect the sensitivity of flaw detection in radiographic testing are the type of specimen, its geometry, shape, thickness and physical density; type, location and orientation of defects with respect to the direction of the beam of radiation; exposure conditions such as energy of radiation, scattering, source-to-film distance, object-to-film distance, source size, filters if used, intensifying screens, etc.; type of film used and the film processing conditions; film viewing conditions and the operator's eye sight, qualifications, skill and experience. Sensitivity is determined through the use of image quality indicators (IQI) of which there are several kinds. The most commonly used IQIs are the wire type which have a number of wires of varying but known diameters placed 5 mm apart in a plastic housing. The wires are, in principle, of the same material as the material under test. These IQIs are placed on the surface of the test specimen facing the source and then the exposure is made and the film processed. The minimum diameter of the wire visible on the radiograph is noted. The sensitivity is calculated from the relationship, S = (diameter of the thinnest visible wire × 100)/(total test specimen thickness). The sensitivity, S, comes out in percentages, e.g. 1%, 2%, 4%, etc.- the lower the value the better the sensitivity of flaw detection. Typical wire diameters of an ISO recommended IQI are given in the Table 7.2.

TABLE 7.2 : WIRE DIAMETERS FOR ISO RECOMMENDED WIRE TYPE IQI.

Wire number	**Diameter (mm)**	**Wire number**	**Diameter (mm)**
1	0.032	12	0.40
2	0.040	13	0.50
3	0.050	14	0.63
4	0.063	15	0.80
5	0.080	16	1.00
6	0.100	17	1.25
7	0.125	18	1.60
8	0.160	19	2.00
9	0.200	20	2.50
10	0.250	21	3.20
11	0.320		

TABLE 7.3 : RECOMMENDED HOLE DIAMETERS AND STEP THICKNESSES FOR IQI.

Step number	Hole diameter and step thickness mm)*	Step number	Hole diameter and step thickness mm)
1	0.125	10	1.00
2	0.160	11	1.25
3	0.200	12	1.60
4	0.250	13	2.00
5	0.320	14	2.50
6	0.400	15	3.20
7	0.500	16	4.00
8	0.630	17	5.00
9	0.800	18	6.30

The other type of IQI is the 'step and hole' type. It consists of a piece of metal having a series of steps of known thickness and each step having a hole drilled through it. The diameter of the hole is equal to the thickness of the step. Table 7.3 gives some typical values for step thickness and hole diameters. The tolerances on these dimensions is ± 5%.

ASME and ASTM have an IQI of their own. It consists of a uniform thickness plate containing three drilled holes and identification letters. If the penetrameter thickness is T, the hole diameters are T, 2T and 4T. Three general quality levels are quoted namely 2-1T, 2-2T and 2-4T. The first number of these refers to penetrameter thickness expressed as a percentage of specimen thickness while the second to the diameter of the penetrameter hole visible in the radiograph expressed as a multiple of the penetrameter thickness. The quality level 2-1T corresponds to 1.4% sensitivity, 2-2T to 2% and 2-4T corresponds to 2.8% sensitivity. Special quality levels include 1-1T, 1-2T and 4-2T which respectively correspond to 0.7, 1.0 and 4% sensitivity.

Evaluation in terms of nature, size and location of defects is done by the careful interpretation of the final radiograph. Interpretation should be done in proper lighting conditions using illuminators having appropriate intensities. The density of the radiograph should be checked and should be within the prescribed limits. Identification of radiographs and sensitivity of IQI are the next things to be established by looking at the radiograph. Thinnest wires or steps and holes visible in the radiograph are noted. Recommended values of sensitivity must be achieved. The final interpretation step is assigning reasons to all the density variations seen in the radiograph. These may be due to external and surface defects, internal defects or the artefacts. The nature of the defects can mostly be seen and

recognized from their pictures in a radiograph. Consideration should, however, be given to the fact that defects of different shapes will give rise to different types of shadows. It is to be remembered that a radiograph gives a two-dimensional picture of a three-dimensional defect. For example, a gas hole which is actually spherical in nature will show up as a circular patch. A crack which actually has a length, width and depth, if detected, will form a line. Pipes and other cylindrical defects will have different shapes in the radiograph depending upon their orientation with respect to the beam direction. If the beam direction is not perpendicular or if the plane of the defect is not parallel to the plane of the film the shadow will be distorted. Because of this distortion sometimes a particular defect can produce a shadow which may be interpreted as some other type of defect. A fine crack may be diffused altogether hardly leaving any image behind. Although before taking a radiograph one may not have any idea about the orientation of the defects present, efforts are usually made to place the film as parallel to the specimen and as normal to the direction of radiation as possible. A number of standard reference radiographs show the typical appearance of defects which can be compared with the images in the radiographs to determine their nature. A description of some typical defects encountered in welding and casting is given hereunder :

(a) Gas inclusions

Gas may develop during welding due to many factors like the quality of the parent metal, the electrodes used, poor regulation of the arc current, etc. The gas may get entrapped and take various forms.

- **Gas pore:** It is a small bubble of gas entrapped within the molten metal. It has a diameter usually less than 1.6 mm (1/16 inch). A group of gas pores is termed porosity. In a radiograph gas pores appear as a bunch of dark spots situated close to each other.

- **Blowhole:** It is similar to a gas pore except that it is a little larger in dimensions. Its radiographic image is also a dark shadow of rounded contour.

- **Pipe or Wormhole:** Some gas inclusions have an elongated form known as wormholes or pipes. They are usually almost perpendicular to the weld surface. They can result from the use of wet powdered flux or from inadequate regulation of the welding current. Another typical form of pipe has the appearance of a branch of a tree. These can be caused by use of wet welding electrodes. In the radiograph these produce circular or elongated shadows depending upon their orientation with respect to the beam direction.

(b) Slag inclusions

Some slag may be entrapped in the deposited metal during its solidification, particularly if the metal fails to remain molten for a sufficient period to permit the slag to rise to its surface. In multipass welding, insufficient cleaning between weld passes can leave portion of the slag coating in place to be covered by subsequent . A particular characteristic of slag inclusions is the 'slag line', intermittent or

continuous. Such slag lines are often accompanied by a pronounced lack of fusion to the base metal.

These give dark indications on the radiograph. The shape of these dark images is generally irregular. Often the image density is variable even approaching that of the sound metal. The contrast of the slag images is lower than that of a gas cavity of the same size. Large isolated inclusions appear as dark shadow of irregular contour. Cluster of small inclusions appear as a group of dark ill-defined spots. Line inclusions appear as a dark shadow with wavy edges along the weld. It is sometimes found along both edges of a run of welding in roughly parallel lines.

Another discontinuity of different origin but of similar radiographic appearance results from irregular deposits on successive passes which leave voids between passes. Such lack of fill can occur, for instance, in welds made in the overhead position.

(c) Tungsten inclusions

Tungsten inclusions are characteristic of the inert atmosphere welding methods. If the tungsten electrode which supports the electric arc comes into contact with the weld metal, some tungsten particles are entrapped in the deposited metal. These may be in the form of small splinters or even as the pieces of the tungsten wire. The tungsten inclusions appear as very light marks in the radiograph.

(d) Lack of root penetration

In butt welding a root opening is usually left at the bottom of the groove (in one-side welding) or at the centre of the weld (in two-side welding). If the opening between the two plates is narrow, it is difficult to achieve complete penetration and fusion at the root of the weld. A void remains in the weld. Such discontinuities can arise from poor bevelling or preparation of the weld groove. It appears in the radiograph as a continuous or intermittent dark line at the centre of the weld seam. It may have both edges straight or one edge straight and the other wavy.

(e) Lack of fusion

This is due to lack of union in a weld between metal and parent metal or between parent metal and parent metal or between weld metal and weld metal. Lack of fusion can be of the following types :

(i) Lack of side fusion

This is caused by a lack of fusion between the weld metal and the parent metal at the side of a weld outside the root. In the radiograph it appears as a dark straight line, of low intensity, with sharply defined edges.

(ii) Lack of root fusion

This is caused due to lack of union between the adjacent faces of the parent metal at the root. In the radiograph it is revealed as a dark straight line of low intensity with sharply defined edges.

(iii) Lack of inter-run fusion

This is caused by a lack of union between adjacent runs of weld metal in a multirun weld. In the radiograph it appears as a faint line with sharply defined edges.

(f) Cracks

Cracks can be defined as a discontinuity produced either by tearing of the metal while in a plastic condition (hot crack) or by fracture when cold (cold crack). In the radiograph the former is revealed as a fine dark line wandering in direction and tapered at the ends, often discontinuous, when the segments are roughly parallel but slightly displaced and possibly overlapping. A cold crack generally appears as a very fine line, straighter, continuous and free from bifurcations.

(g) Undercut

During the final or cover pass the exposed upper edges of the bevelled weld preparation tend to melt and to run down into the deposited metal in the weld groove. The result is a groove which may be either intermittent or continuous, with more or less sharp edges along the weld reinforcement. The radiographic image of undercut is a dark line of varying width and extent with usually diffused edges occurring at the sides of the weld. The image density indicates the depth of the undercut.

(h) Concavity at the root of the weld

A concave surface at the root of the weld can occur specially in pipe welding (without a cover pass on the root side). In overhead welding this condition is a consequence of gravity which causes the molten metal to sag away from the inaccessible upper surface of the weld. It can also occur in the downhand welding with a backing strip at the root of the weld groove if slag is trapped between the molten metal and the backing strip. This is shown by a broad dark line at the centre of weld image having unsharp edges unlike the edges of lack of penetration.

(i) Change of electrode

At points where the electrodes are changed while making the cover pass, an unskilled welder may choose the wrong position for starting the new electrode. Sometimes slag inclusions occur at the point at which electrodes were changed. The radiograph shows a crescent shaped image corresponding to the point of change of electrode.

(j) Excessive penetration

In welds, sometimes, molten metal runs through the root of the weld groove producing an excessive reinforcement at the back side of the weld. In general this is not continuous but has an irregular shape with characteristic hanging drops of the excess metal. Excessive penetration will be shown as a line of lowered image density in the centre of the weld.

(k) Electrode spatter

If improper electrodes or long arcs are used, droplets of molten metal are spattered about the weld region. These drops stick to the metal surface near the weld seam. Since they correspond to local areas of increased thickness, a series of light round spots appear on the radiograph.

(l) Grinding marks

When weld reinforcements are not ground out smoothly, the resultant thickness varies above and below that of the base metal. In the radiograph it may appear as extended light or dark areas with diffused edges extended over the welded area or the parent metal.

(m) Void

'Void' is defined as a cavity produced by:

(i) Entrapped gas evolved from the metal
(ii) Entrapped air
(iii) Entrapped gas evolved from the mould
(iv) Shrinkage of metal.

Voids have been classified depending on their shape and size. The classes are described below :

- **Microporosity:** A fine form of the defect due to shrinkage or gas or both in which a number of cavities occur either around the grain boundaries (intercrystalline) or between the dendrite arms (inter-dendritic). In a radiograph this usually produces a general mottled or cloudy effect. In non-ferrous alloys the fine cavities may occur in layers (layer porosity) and produce dark streaks in the radiograph.

- **Sponginess:** A system of inter-crystalline or interdendritic cavities of a coarse and usually localised form which appear in a radiograph as a group of dark interconnected images which may be irregular in outline and varying in size and blackness.

- **Airlock:** A cavity formed by air which has been entrapped in the mould by the metal during pouring. The defect appears in a radiograph as a dark area with a generally smooth outline but may have discontinuities.

- **Shrinkage cavity:** A discrete cavity caused by contraction during solidification. The radiographic appearance is similar to that of a gas hole but usually shows a less regular outline and may tend to taper.

- **Filamentary shrinkage:** A coarse form of shrinkage defect in which the cavities are branching, interconnected and extensive. In the radiograph the images appear as continuous, irregular, dark, usually branched or occasionally in the form of a network.

(n) Cold shut

It is a discontinuity caused by the failure if a stream of molten metal to unite with a confluent stream or with solid metal, such as a chaplet, internal chill or pouring splash. This may often be caused if the pouring is interrupted. Usually it appears as a dark line. A cold shut arising from a splash in the mould may appear as a dark crescent or circle.

(o) Segregation

Segregation is a condition resulting from the local concentration of any of the constituents of an alloy.

- **General segregation**: It extends over a considerable part of a casting. Radiographically it appears as an assemblage of small light or dark areas.

- **Local segregation**: Occurs when the shrinkage voids or hot tears are wholly or partially filled with a constituent of low melting point. It appears in a radiograph as light or dark areas coinciding with the original defect.

- **Banded segregation:** This is mainly associated with centrifugal castings but can occasionally occur in static casting also. Radiographically it appears as alternate light or dark bands.

The size of the defects can be measured from the radiographs keeping in view the factors of film type, screens, source size and energy, source-to-film distance and orientation, etc. Finding the location of the defects within the test specimen is, however, cumbersome with radiography. Therefore the question of location of internal defects is mostly settled by requesting ultrasonic testing. Nevertheless radiographic techniques exist for this purpose and these will be described for the sake of completeness of the subject. An image formed at point C, Figure 7.1, in a radiograph may be due to a defect located anywhere on the line AB parallel to the beam direction. One radiograph cannot, therefore, reveal the position of the defect in the third dimension. The following methods can be used to locate a defect in three dimensions.

If the dimensions of the specimen permit, two radiographs are made from two positions at right angles to each other as shown in Figure 7.2 . Either of the two radiographs will give the position of the defect in two dimensions while the other radiograph will provide the third dimension. This method is the simplest yet very

accurate. The limitation is that at least two dimensions of the specimen should be such as to make the radiograph possible with the available radiation.

Another method which is specially suitable for plate like objects and in situations where the right angle method is not possible is the tube shift method, which is described below:

(i) A normal radiograph is made and the two dimensional position of the defect is marked on the top of the specimen.

(ii)Two exposures are made on the same film, each of approximately half the total exposure at a known sfd. Between these exposures the tube is shifted through a measured distance in a plane parallel to the film and across the larger dimension of the defect (Figure 7.3).

(iii)After processing, the shift of the image of the defect is measured.

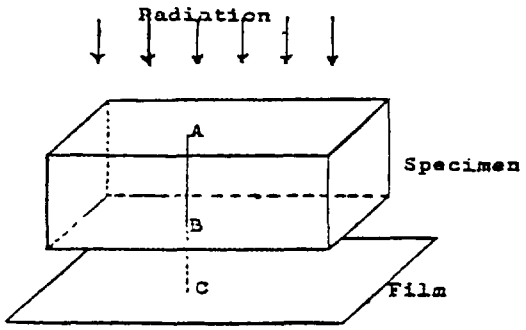


Figure 7.1 : Two dimensional shadow formation of a defect.

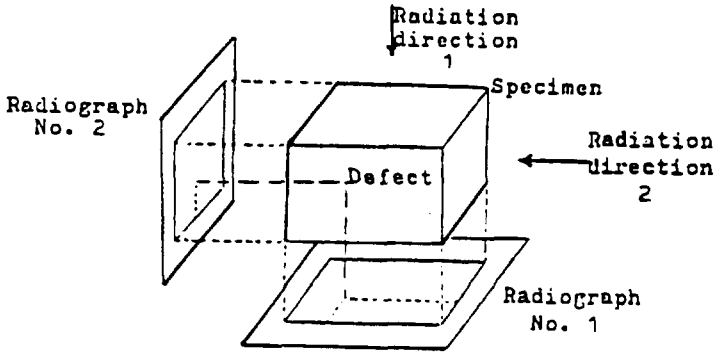


Figure 7.2 : Right angle method for location of internal defects.

Let

S = total tube shift
D = sfd (measured along the normal)
I = image shift
d = height of the defect above the film

For similar triangles we have

$$S/I = (D-d)/d = D/d - 1$$

or

$$d = DI/(S + I)$$

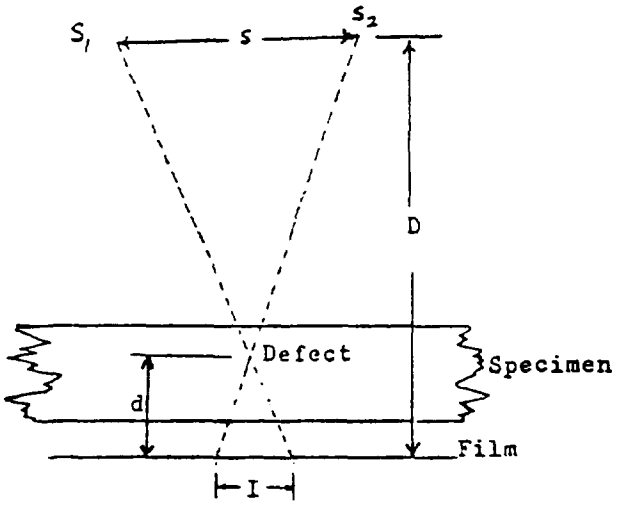


Figure 7.3 : Tube shift method.

To find out the height of the defect above the bottom of the specimen one can subtract the thickness of cassette and the screen, if used, from d. The tube shift should not be too large or too small as this may distort the images or may result in insufficient separation of the images making the measurement of the image shift more difficult. A suitable value may by 1/3rd of sfd.

The third and the most common method of defect location is the lead marker method. The procedure is somewhat similar to the tube shift method but in this case the tube shift and the sfd need not be measured. The method is as follows.

(i) Make a normal radiograph and mark the two dimensional position of the defect on the top of the specimen.

(ii) Two lead markers (fine wires of lead or of any other heavy metal) are placed one on the source side of the specimen and the other on the film side near to and along the length and on either side of the defect. Care must be taken that the images of the defect and markers do not coincide or get mixed (Figure 7.4).

(iii) Two exposures are made on a single film, each of half the total exposure. Between these exposures the tube is shifted through a distance in a plane parallel to that of the film and across the length of the defect (Figure 7.4).

(iv) After processing, the shifts of the images of the defect and the markers are measured.

It can be shown that, provided the markers are placed fairly close to the defect, the image shifts of the defect and markers are proportional to their distances from the film. The thickness of the markers is considered to be negligible.

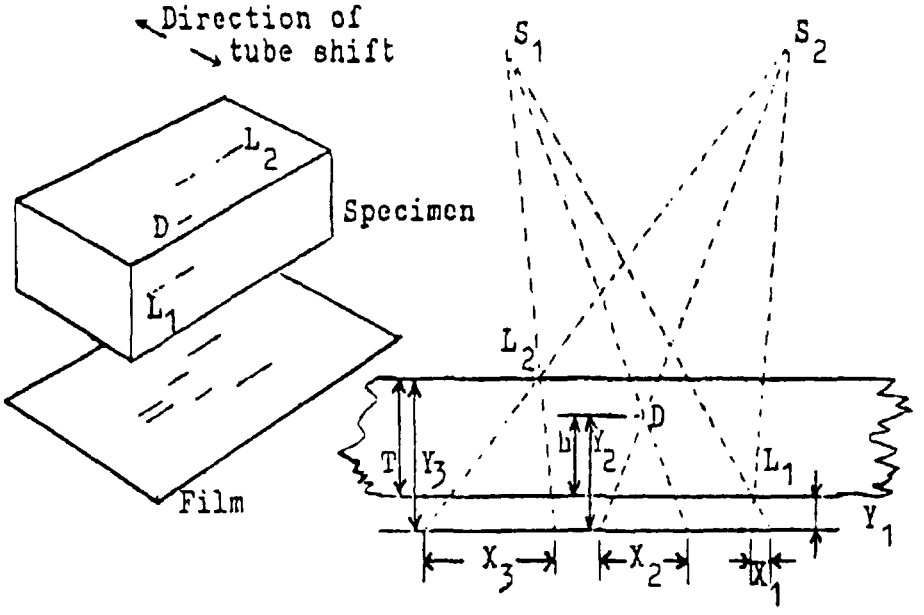


Figure 7.4 : Lead marker method.

Let h = height of the defect above the bottom of the specimen and X_1, X_2 and X_3 be images shifts of lower marker, defect and upper marker respectively.

Y_1, Y_2 and Y_3 be heights above the film of the lower marker, defect and upper marker respectively.

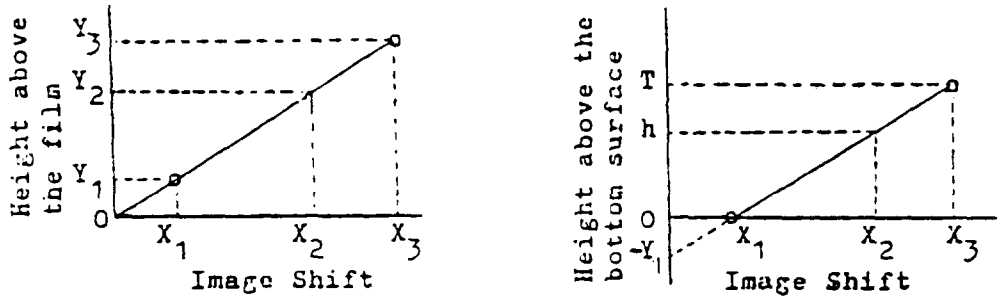
A straight line is obtained (Figure 7.5 (a)) when the height above the film (Y) is plotted against the image shift (X) for the two markers. From this graph height of the defect above the film can be read against the image shift of the defect.

A better and more practical way is to plot the height above the bottom surface of the specimen against the image shift (Figure 7.5 (b)). This eliminates the measurement of the thickness of cassette and screens. In this case the height of the lower marker is zero and that of the upper one is T (thickness of the specimen).

From Figure 7.5 one can find out the height 'h' of the defect from the bottom of the specimen, if its image shift (X) is known. 'h' can also be calculated by the formula:

$$h = T.(X_2 - X_1)/(X_3 - X_1)$$

Stereo radiography is yet another method used for location of defects. Two radiographs of the specimen are taken from two slightly different directions. The angle between these directions is the same as the angle subtended by the human eyes while viewing these radiographs. In the stereo viewer the left eye sees one radiograph and the right eye the other. In this way a realistic three dimensional effect is obtained giving the visual assessment of the position of the defect.



(a) (b)

Figure 7.5 : Height vs image shift.

7.2.5 Ultrasonic testing

The sensitivity of flaw detection for ultrasonic testing method is dependent upon the type of the specimen, its geometry and shape, grain structure and surface condition; nature, type, orientation and location of defects; probe characteristics such as frequency, dead zone, near zone and beam divergence; viscosity and acoustic impedance of the couplant; equipment characteristics such as range, resolution and pulse shape; calibration test blocks and procedures; scanning and evaluation procedures and the operator qualifications, skill and experience.

An ultrasonic flaw detector must be set at a minimum level of sensitivity since this is the only means whereby echoes of otherwise uncertain significance can be translated into meaningful information. In principal the choice of a sensitivity level is based on the reflectivity of the smallest flaw that is to be found at the maximum test range.

Two sensitivities are used during an inspection, the evaluation sensitivity and the scanning sensitivity. The evaluation sensitivity (or reference sensitivity) are the instrument settings which produce a reproducible signal amplitude from a reference artificial reflector with which the instrument settings relating to a discontinuity echo can be compared. The evaluation sensitivity can also be called

the primary reference echo (PRE) level. Scanning sensitivity is used during the preliminary scanning of a test piece to locate all discontinuity echoes which have to be assessed at the evaluation sensitivity. It is set by increasing the amplification of the instrument from the evaluation sensitivity instrument settings by a specified amount, e.g. 6dB. The commonly used methods of setting evaluation sensitivity are described below in a brief manner :

The distance amplitude correction (DAC) method which is used for instance in the ASME code in which echo heights from similar size artificial reflectors in a reference block are plotted on the CRT screen to compensate for attenuation of the signals with increasing distance from the probe. The DAC curve shows how the echo heights from the same sized flaw would decrease with distance from the probe within the test specimen. The DAC curve line represents the reference level (PRE). Lines may also be drawn at 50% or 20% of this reference level. Transfer loss is then calculated between the reference block and the work piece and is added to the DAC gain. For initial scanning the sensitivity is then set at twice (i.e. +6 dB) the reference level plus transfer loss. The evaluation of flaws for acceptance or rejection is however carried out with the gain control set at the PRE level plus the transfer loss.

The DGS (distance-gain-size) diagram method makes use of the so called DGS diagram, developed by Krautkrämer in 1958 by comparing the echoes from small reflectors, namely different diameter flat bottom holes located at various distances from the probe, with the echo of a large reflector, a back wall reflector, also at different distances from the probe. The difference in the amplitude of echoes of the flat bottom holes and the back wall reflector is determined in decibels i.e. dB.

The DGS diagrams relate the distance D from the probe (i.e. along the beam) in near field units, thus compensating for probes of different size and frequency, to the gain G in dB for a flat bottom hole compared to a particular back wall reflector and the size S of the flat bottom hole as a proportion of the probe crystal diameter (see Section 3.6.3).

Since in the case of angle beam probes some of the near field length is contained within the perspex path length and this varies for different designs and sizes of probes, individual DGS diagrams are drawn for each design, size and frequency of angle beam probe.(For this reason the scale used in the angle beam probe DGS diagrams is simplified: The D-scale is calibrated in beam path lengths, the G-scale in decibels as before; and the S- scale representing flat bottom hole or disc shaped reflector diameters in mm).

Finding the grain response on the time base of the CRT screen at the maximum testing rate is another method for setting test sensitivity. In this method the gain controls of the flaw detector are so adjusted that "grass" (i.e. echoes caused by the metallurgical structure of the test specimen) is produced over the full testing range. For weld joints, for example, the target for setting the sensitivity using this method may be the under surface of the parent material. A change in the sensitivity may now be required during the scanning to facilitate the exploration of defects. In any case, the change in gain is to be noted in decibels.

Sensitivity may also be set in terms of the echo height from a 1.5 mm drilled hole in a standard test block or any other reference surface such as the back wall from an IIW calibration block. The echo height can be set to a convenient value, say 75% of full screen height and the gain values for this noted.

Characterization of the defects for their nature, size and location with the help of ultrasonics is done using a properly calibrated testing system. In this properly calibrated system the distances on the CRT screen time base are proportional to the distances in the test specimen. Therefore from the location of the defect echoes on the screen the distance of the defect within the specimen from the probe position on the test surface can be directly determined (Section 3.6.1). For the normal beam probes this will indicate the depth of the defect below the test surface while for angle probes the depth below the test surface can be calculated from a knowledge of the probe angle and the distance between the defect and the probe position.

The commonly used methods for flaw sizing in ultrasonic testing are 6 dB drop method, 20 dB drop method, maximum amplitude method and DGS diagram method and some others. The basic assumption in the 6 dB drop method is that the echo height displayed, when the probe is positioned for maximum response from the flaw, will fall by one half (i.e. by 6 dB and hence the name) when the axis of the beam is brought into line with the edge of the flaw as illustrated in Figure 7.6 .The method only works if the ultrasonic response from the flaw is essentially uniform over the whole reflecting surface. The procedure to determine the dimension of a flaw parallel to the probe movement i.e. the flaw length is as follows:

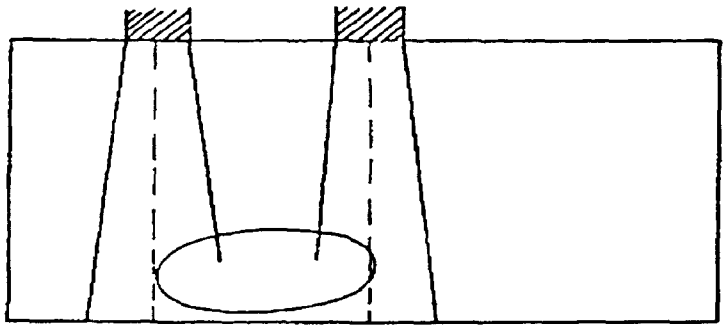


Figure 7.6 : Defect sizing using the 6 dB drop method.

i) Position the probe to get maximum echo from the flaw.

ii) Adjust the height of the echo to some convenient scale on the CRT screen by using the gain control of the flaw detector.

iii) Move the probe across the flaw in one direction until the echo height falls to one half of the height adjusted in (ii).

iv) Mark the centre of the probe on the surface of the test specimen for this probe position.

v) Now move the probe in the opposite direction through the maximised echo position to the position when the echo height again falls to one half of the height adjusted in (ii).

vi) Mark the probe centre at this position as well.

vii) The distance between the two marks gives the dimension of the defect parallel to the probe movement. If the reflectivity of the flaw varies considerably the probe is moved until the last significant echo peak is observed just before the echo drops off rapidly. This peak is brought to full screen height and then the probe is moved as in (iii). A similar procedure is followed for the other end of the flaw.

The 6 dB drop method is suitable for the sizing of flaws which have sizes of the same order or greater than that of the ultrasonic beam width but will give inaccurate results with flaws of smaller sizes than the ultrasonic beam. It is therefore generally used to determine flaw length but not flaw height.

The 20 dB drop method utilises, for the determination of flaw size, the edge of the ultrasonic beam where the intensity falls to 10% (i.e.20 dB) of the intensity at the central axis of the beam. The procedure to determine the size of the flaw with the 20 dB drop method is as follows:

i) Position the probe to get a maximum echo amplitude from the flaw.

ii) Adjust the echo amplitude to some convenient scale on the CRT screen using the gain control of the flaw detector.

iii) Move the probe first across the flaw in one direction until the echo amplitude falls to 1/10th of its original height (i.e. by 20 dB) as in (ii).

iv) Mark the position of the probe index on the surface of the test specimen at this position.

v) Now move the probe in the opposite direction through the maximised echo position until the echo amplitude again falls to 1/10th of its original height as in (ii).

vi) Mark the position of the probe index on the surface at this position as well.

vii) Measure the distance between the two markings.

viii)Determine the beam width 'W' at the depth 'd' of the flaw from the beam profile diagram or from the equation.

$$W = D + 2 (d - X_o) \tan \phi$$

where

W = Beam width
d = Defect depth
X_o = Near field length
D = Probe diameter
ϕ = Angle of beam spread

ix.) (vii) minus (viii), as illustrated in Figure 7.7 will thus give the dimension of the flaw parallel to the movement of the ultrasonic beam.

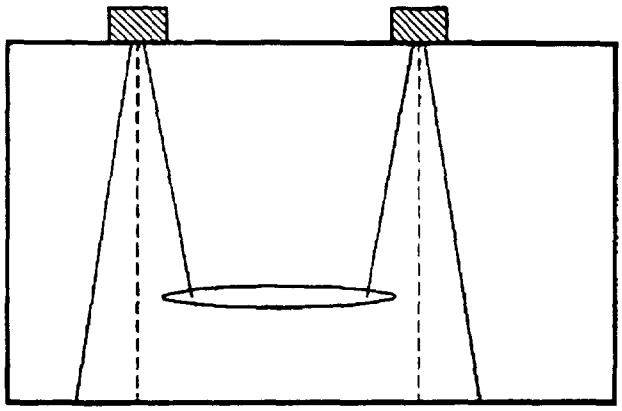


Figure 7.7 : 20 dB method of defect sizing.

As for the 6 dB drop method if the echo amplitude varies as the probe is traversed across the flaw the 20 dB drop should be carried out from the last significant echo peak. The 20 dB drop method gives more accurate results than the 6 dB drop method because of the greater control one has on the manipulation of the ultrasonic beam. However, size estimation using either the 6 dB or 20 dB drop methods have inherent difficulties which must be considered. The main problem is that the amplitude may drop for reasons other than the beam scanning past the end of the defect.

1. The defect may taper in section giving a reduction in cross sectional area within the beam. If this is enough to drop the signal 20 dB or 6 dB the defect may be reported as finished while it in fact continues for additional distance.

2. The orientation of the defect may change so that the probe angle is no longer giving maximum response - another probe may have to be used.

3. The defect may change its direction.

4. The probe may be twisted inadvertently.

5. The surface roughness may change.

The maximum amplitude method takes into account the fact that most defects which occur do not present a single, polished reflecting surface but in fact take a rather ragged path through the material with some facets of the defect surface suitably oriented to the beam and some unfavourably oriented. Figure 7.8 illustrates this phenomenon showing a crack propagating in a weld. Each of the reflecting facets will be at a slightly different range, and although they may be too close together to resolve as separate echoes, the echo envelope can nevertheless be regarded as a series of overlapping separate echoes. In fact the envelope may look like Figure 7.9 (a, b) or c depending on the degree of range variation from the different facets and on the resolution of the equipment. As the beam is scanned across the surface of the defect, the beam centre will sweep each in turn. As it does, the echo from that facet will reach a maximum and then begin to fall, even though the main envelope may at any instant, be rising or falling in echo amplitude. The stand-off and range of the maximum echo of each facet is noted and plotted on the flaw location slide. This results in a series of points which trace out the extent of the defect. The gain is increased to follow the series of maximum echoes until the beam sweeps the last facet.

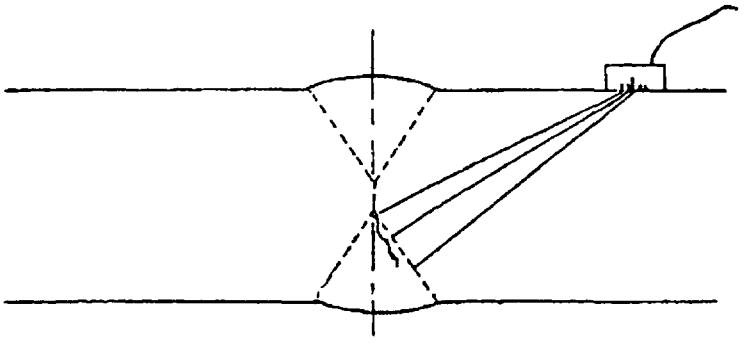


Figure 7.8 : Illustration of ragged weld crack.

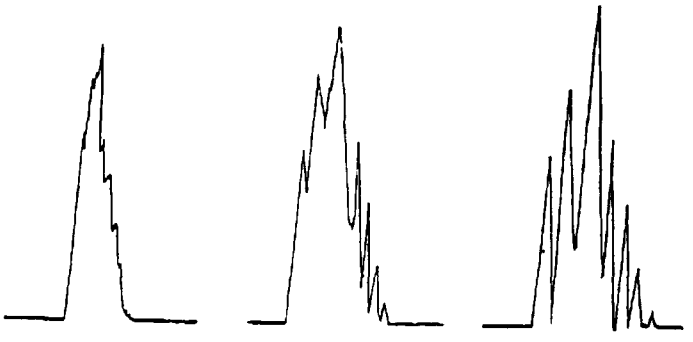


Figure 7.9 : Response from weld crack.

The universal DGS diagram for normal beam probes, which can be used for any normal beam probe irrespective of the size and frequency of the probe, is shown in

Figure 7.10. This diagram relates the distance D from the probe (i.e. along the beam) in near field units thus compensating for probes of different size and frequency, to the gain G in dB for a flat bottom hole compared to a particular back wall reflector and the size S of the flat bottom hole as a proportion of the probe crystal diameter.

Since in the case of angle beam probes some of the near field length is contained within the perspex path length and this varies for different designs and sizes of probe, individual DGS diagrams are drawn for each design, size and frequency of angle beam probes. For this reason the scale used in the angle beam probe DGS diagrams is simplified. The D-scale is calibrated in beam path lengths, the G-scale in decibels as before and the S-scale representing flat bottom hole or disc shaped reflector diameters in mm.

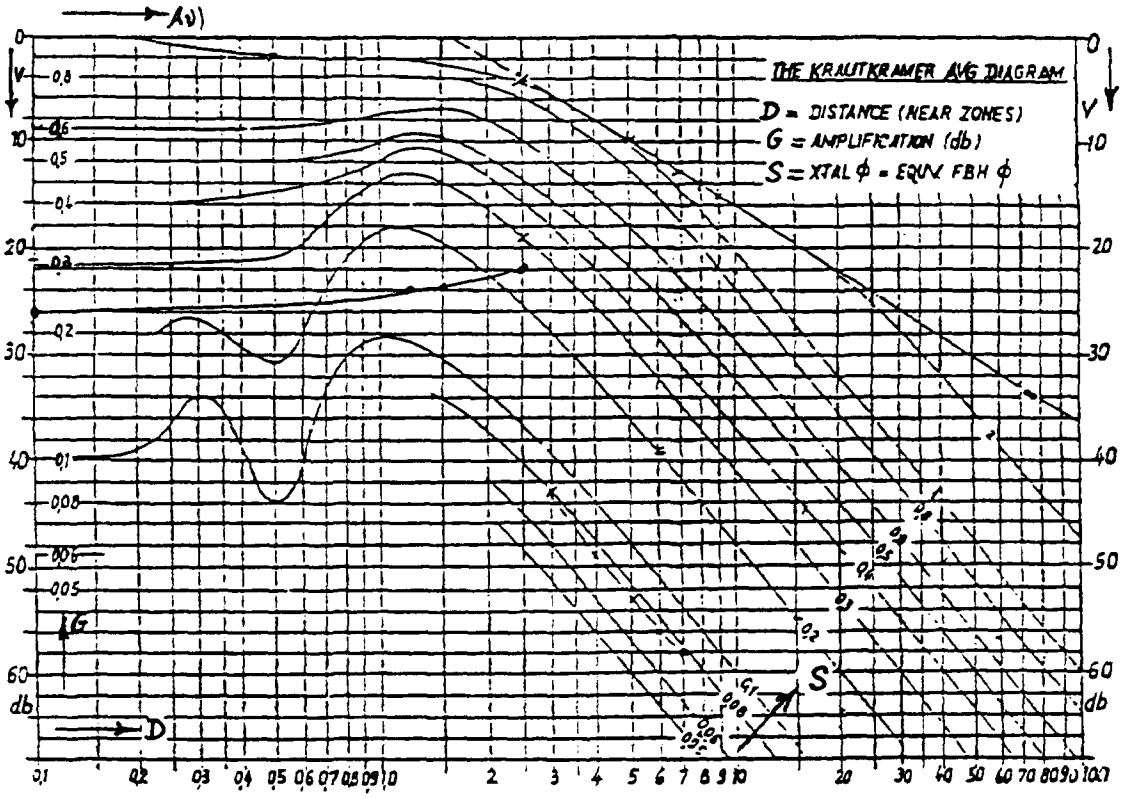


Figure 7.10 : Universal DGS diagram for a normal beam probe.

7.3 ACCEPTANCE AND REJECTION CRITERIA

After the prescribed tests have been completed and the flaws characterized according to their nature, size and location the next question is how to treat the flaws. Some careful considerations in this respect need to be made. The sensitivity of flaw detection is ever increasing with improvements in instrumentation. This is the case, for example, with radiographic testing where at one time sensitivity was of the order of 5% meaning that flaws in the range of 5% of the test specimen thickness could possibly be detected. At that time then defects of this order were

being detected and rejected. Now the sensitivities in the range of 0.5 or 1.0% are obtainable which have brought down significantly the level of flaws that can be detected. Similarly in the case of ultrasonic testing there was a time when people were happy to have cracked areas the size of their palm reliably reported. This has been improved over the years so that areas the size of their fingernail have been reliably reported and now with modern equipment we can detect areas of discontinuity say 1 mm by 1/8 mm. A further example is the assessment of the impressions, dents, gouges and corrosion pits. The availability of improved wall thickness measuring devices with a sensitivity of 0.1 mm and better has led to tighter surface and mensuration inspection so that more materials are re-cycled than previously. This is in spite of research work which shows that corrosion pits of certain sized areas may be down to 20% of the wall thickness and be not harmful, a result which seems to be backed up by field experience. Now whether such small flaws and thickness variations which are now within the detection capability of various NDT methods should be rejected would remain a matter of subjective judgement unless it is fully established by calculations and extensive experimentation that this level of flaws is really going to be dangerous and therefore parts containing these sorts of flaws should not be allowed to go into service until after their satisfactory rectification. It must also be recognised that irrespective of the non-destructive tests employed, a discrete small percentage of defects will go unreported. Of course, all industrial construction depends to some extent upon a statistical probability of failure, and the job of overall quality assurance is to ensure that the level of this failure probability is kept acceptably low. Except in the most extraordinary circumstances,100% non-destructive inspection with all the available techniques would never be specified, and of course, even if it were, it would not guarantee 100% freedom from imperfections. In practice, therefore, adequate levels of quality assurance can only be obtained through the development of an integrated system of production control and NDT. These and many other considerations have gone into preparing acceptance/rejection standards for various products usually tested with non-destructive testing methods. The most serious defects from the loss of strength point of view are planar defects, such as cracks and lack of fusion, and that volumetric defects, such as gas holes, are less serious. It is now clear that the through thickness dimension of a defect is more significant than the defect length, and also that surface-breaking defects are more serious than totally internal defects. There is ample evidence that distributed porosity has very little effect on weld strength. As a consequence of these findings, the acceptable levels for weld defects is a constantly changing topic, still subject to much discussion and controversy.

To establish acceptance/rejection criteria, it may be necessary to conduct an extensive correlation study between non-destructive test indications and destructive test results. This is the ultimate procedure, but even this may leave some doubt since flaws or indications do not always occur in exactly the same place, with the same frequency, or to the same extent. It should be obvious that a number of factors enter into the final judgement and should be considered while attempting to arrive at an accept/reject criterion. Some of these are:

1. The metal or alloy involved in test objects.

2. If the test objects have a non-metallic surface, the composition of the non-metal.

3. The location of the indications, e.g., are they (a) in critical radii, (b) on edges that will be ground off, (c) in parts designed for high strength applications, or (d) in thick sections which may allow for removal of surface defects without sacrifice of function?

4. Whether or not the surface or surfaces are repairable by welding or other means.

5. The cost of the part. (It may be that the cost of a new part is so low that the expense of repair or rework of a defective part is not warranted. Conversely, of course, one would not want to discard an expensive piece of hardware that could be reworked at a considerable saving over the cost of a new part.)

Inspection acceptance/rejection criteria for parts or surfaces would normally be referenced by an applicable specification, standard for a particular part, or some other governing document that would outline what type of discontinuity would be the cause of rejection. An extreme example of this would be the approach taken by companies that are working with fracture mechanics, whereby a particular structure or part is analysed for specific types of discontinuities that may or may not constitute a defect. Standards are then drawn up for the items for non-destructive test criteria.

A number of standards exist prescribing some sort of accept/reject criteria and these are briefly described hereunder :

7.3.1 Liquid penetrant testing

The American Society for Testing and Materials (ASTM) has issued ASTM E43375,Standard Reference Photographs for Liquid Penetrant Inspections. This publication contains reference photographs to be used as a means of establishing and classifying type and characteristic of surface discontinuities detectable by penetrant inspection methods. They may be used as a reference for acceptance standards, specification, and drawings. However, no attempt has been made to establish limits of acceptability or the extent of the metallurgical discontinuity.

When it has been determined that an indication is relevant, a further judgement must be made as to the disposition of the test objects to answer questions such as:

1. Should supplemental non-destructive tests such as ultrasonic or X ray be used to attempt more complete definition of the discontinuity causing the penetrant indication?

2. Can the surface be accepted as it is, or be reworked to eliminate the indicated discontinuity?

3. Should the surface or part be discarded as unserviceable?

Specifications or drawings for the parts or surface under examination should specify the non-destructive test methods required for part acceptance. Moreover, drawings should specify the acceptance or rejection criteria or refer the inspector to supplemental documents such as applicable acceptance/rejection specifications. If penetrant inspections are being made on critical parts such as nuclear hardware or a jet engine component, an expert in evaluation of indications in the specific industry may have to be called upon for a judgement. The accept/reject criteria for penetrant testing would include minimum acceptable indication size and strict uniform penetrant processing. In some cases, specifications provide a guide to parts evaluation based primarily upon the size, shape, or location of penetrant indications. For such purposes, a linear penetrant indication is defined as having a length greater than three times the width. Rounded penetrant indications are those that are circular or elliptical with the length less than three times the width. In some code applications, unacceptable defects are then defined in terms such as:

1. Any crack or linear indication.

2. Rounded indications greater than 5 mm (or 3/16 in.) in dimension.

3. Four or more rounded indications in a line separated by 1.5 mm (or 1/16 in.) or less, edge to edge.

4. Ten or more rounded indications in any 15cm square of surface with the major dimension of this area not to exceed 15 cm. The area must be taken in the most unfavourable location relative to the indications being evaluated.

Similar criteria are laid down by the aerospace for different components such as castings, extrusions, forgings, formed parts, heat treated parts, machined parts, plates, sheets and turbine blades; for ships and submarines. Some variations in the accept/reject criteria exist from case to case and therefore only relevant standard of the latest revision should be used for this purpose.

7.3.2 Magnetic particle testing

Most of the arguments listed under liquid penetrant testing should in principle be also valid for magnetic particle testing. When multiple variables can affect the outcome of a test a means should be used to normalize or standardize the test. This ensures that consistent, repeatable results are achieved independent of the machine, the operator or the time of the test.

The most direct way to achieve consistent results is to regularly use a reference standard to compare system's sensitivity to pre-established tolerances. If the desired sensitivity is not achieved, testing should be stopped to allow required system adjustments. The standard may be an actual test object with known discontinuities; a replica with discontinuities; a magnetic field indicator; a tool steel ring; an artificial discontinuity or shim standard or a tangential field meter with an associated reference standard. Acceptance criteria for test objects shall be incorporated as part of the written procedure whether specifically or by reference to other documents containing the necessary information. Methods for establishing

acceptance requirements for large crankshaft forgings are discussed in ASTM A456. Methods for establishing requirements for steel forgings are discussed in ASTM A275. Methods for classifying castings are given in MIL-STD- 2175. MIL-M-47230 provides a classification scheme for ferromagnetic forgings, casting, extrusions and weldments. The testing of aircraft steel for cleanliness using magnetic particle testing is discussed in AMS 2300, AMS 2301 or AMS 2303 as appropriate to the type of steel being tested. Military Standard on Surface Inspection Acceptance Standards for Metals (NAVSHIPS 0900-003-8000) is used widely throughout U.S. Navy shipbuilding. In general, the acceptance criteria for weld magnetic particle testing is "no linear indications over 1/16 inch (1.5 mm.)" ASME Section VIII requirements for magnetic particle inspection are somewhat more stringent in that all linear indications must be removed but no definition of linear is given. The magnetic particle acceptance requirements for the U.S. Navy are somewhat less stringent.

7.3.3 Eddy current testing

The usual accept/reject decision is exercised with the help of reference standards. Reference standards simulate the parts to be inspected except they contain discontinuity criteria. The physical, electrical and magnetic characteristics of a reference standard must represent: (1) what is expected of the population of parts; and (2) what the test process is sensitive to. The reference standard should be a stable device with stable characteristics from which the performance of the electromagnetic test can be established and evaluated.

If the total surface of each part is to be tested, then the reference standard must duplicate the total part. If only a portion of a part is to be tested, then the reference standard need only duplicate that portion of the part , providing a reliable means to properly locate the tested portion in a holding fixture. If the dimensions of the part have tolerances, then the reference standard should be of average size. If there is a possibility that an out-of-tolerance surface may mask a discontinuity, then a pretest inspection should ensure that those out-of-tolerance parts are removed before testing, or the holding fixture may be made to reject the out-of-tolerance parts. If the surface finish of a part influences the test results, then the reference standard should have an average surface finish of the specified tolerance. If the value of magnetic permeability varies, then the reference standard should have an average value of magnetic permeability.

Reference standards can be made with known defects such as cracks, notches or drilled holes. The critical values of these defects are separately determined using destructive testing and fracture mechanics under the simulated service conditions. The reference standard is then used to adjust the electromagnetic equipment's sensitivity to various specimen parameters (cracks, surface roughness, conductivity and permeability variations, etc.). Consistency of calibration is maintained through the use of procedural documents such as those by the American Society for Testing Materials, the American Petroleum Institute, government military specifications or other. In actual testing the specimens tested to contain defects of the order of or greater than the critical size of defects in the reference standards are rejected. In some applications, there is no need for

acceptance reference standards. The integrity of the eddy current test equipment depends on accepting good parts. In these cases, the purpose of the reference standard is to establish and maintain sensitivity to discontinuities. Therefore, only rejection reference standards for both set up and calibration functions are needed. Calibration reference standards should be used to verify the accuracy of an eddy current test before a group of tested and accepted parts are released. A caution has also to be exercised in rejecting the tested parts in view of the great sensitivity and accuracy of detection that can be achieved with eddy current testing.

The acceptance and rejection criteria in eddy current testing vary in accordance with the type of test specimens. This will be illustrated with the help of some examples :

When using the absolute encircling coil method, the known acceptable calibration standard is inserted in a fixed position in the coil and the test instrument is adjusted to achieve an on-scale meter reading, an oscilloscope reading or both. The acceptable standard is replaced in the exact position with a known unacceptable standard and the sensitivity of the instrument is adjusted to maximize the indicated difference reading without exceeding 90 per cent of the available scale range. When using the comparative encircling coil method, a reference piece is selected (usually one that falls within the acceptable limits of the specimens being tested) and placed in the reference coil. This coil and the reference piece are placed in location where they will not be accidentally disturbed during the sorting operation. The procedure with probe coils is similar to that used with encircling coils. Instead of placing standards in the coils, however, the probe is positioned in a consistent, suitable location on the standard.

7.3.4 Radiographic testing

In general two methods are used to give the acceptable quality of defects. The first refers to the reference radiographs, the other gives maximum dimensions of acceptable defects. Both methods have this in common that they are based on radiography.

7.3.4.1 Reference radiographs

Such radiographs are available for casting as well as welding. The application of the ASME SE-390 Standard Reference Radiographs for Steel Fusion Welds is as follows:

(i) The graded reference radiographs may be used in whole or in parts as applicable to particular requirements.

(ii) The length of the welding to which the selected standard applies shall be established. These designated lengths shall not contain any discontinuity whose severity exceeds that in the reference.

(iii) When the production radiograph is interpreted as showing equal or less severe discontinuation than the selected standard the weld shall be judged

radiographically acceptable. When the production radiograph is interpreted as showing greater severity than the selected standard, the weld shall be judged unacceptable and shall be repaired in accordance with contractual agreements.

(iv) If more than one type of discontinuity occurs in the same radiograph, the predominating type alone governs acceptability unless the severity represented by the combination of discontinuity types is such as to make the overall condition unacceptable for the intended application.

(v) When two or more discontinuity types are present in the same radiograph to an extent equal to the maximum acceptable for two of these types the weld shall be judged unacceptable, with repair welding to be done according to contractual agreement.

(vi) When repair welding is permitted, the repair need only be to that extent which will bring the weld quality to within the acceptable reference.

7.3.4.2 Acceptance by dimensions of defects

In the ASME boiler and pressure vessel code (Sections I, III, VIII) the following acceptance standards are given. Sections of weld that are shown by radiograph to have any of the following types of imperfections shall be judged unacceptable and shall be repaired and the repair radiographed:

1. Any type of crack, or some of incomplete fusion or penetration.
   - 6.35 mm for thickness t up to 19 mm
   - 1/3 t for t between 19 and 57 mm
   - 19 mm for t > 57 mm

2. Any group of slag inclusion in line that has an aggregate length greater than t in a length of 12 t, except when the distance between the successive imperfections exceeds 6 L where L is the length of the longest imperfection in the group.

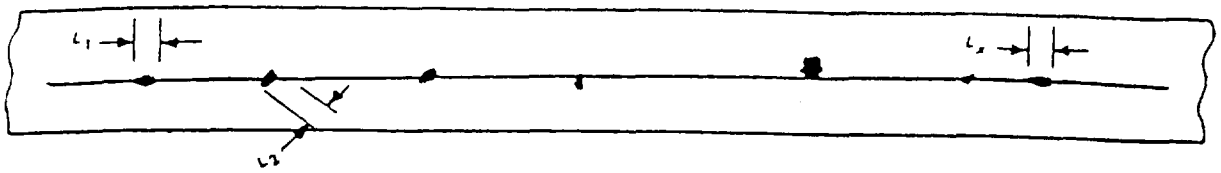
In case of round shaped defects the maximum permissible size of any indication shall be ¼ t or 5/32 in (3.96 mm), whichever is less; except that an isolated indication separated from an adjacent indication by 1 in (2.54 mm), or more may be 1/3t or 1/4 in (6.35 mm), whichever is less. For t greater than 2 in (50 mm), the maximum permissible size of an isolated indication shall be increased to 3/8 in (9.5 mm). Aligned rounded indications are acceptable when the summation of the diameters of the indications is less than t in a length of 12 t (Figure 7.11 (a)). The length of groups of aligned rounded indications and the spacing between the groups shall meet the requirements of Figure 7.11 (b). Similarly charts are given for evaluation of rounded indications in different thickness ranges and for non-aligned indications as well as for clustered indications.

The British Standard BS 5500 also gives a detailed accept/reject criterion for different categories of construction. The concepts are more or less similar to those of ASME. Defects such as cracks, lamellar tears, lack of fusion and lack of penetration to any extent are not permitted while for other types of defects the

ranges of acceptance are specified. The reader is recommended to have a look at the above standard if more details are desired. Similarly criteria are also available for casting and forging.

7.3.5 Ultrasonic testing

In ultrasonic testing of welds, the situation is much more complex in that the nature of the defect is not always identified. Until recently, radiographic-type codes of acceptance have been used, but there have been attempts to redraft these in purely ultrasonic terms. Again, a distinction between quality control and fitness-for-purpose criteria is made, and three classes, I to III, of inspection are proposed, class III being the most stringent. Fitness-for-purpose criteria are based on a fracture mechanics approach, which presupposes a knowledge of the applied stresses in service. For this approach, the through-thickness dimension of the defect is the critical parameter to be determined. In ultrasonic testing, the following data are usually available:



Sum of L_1 toL_x shall be less than t in a length of 12t.

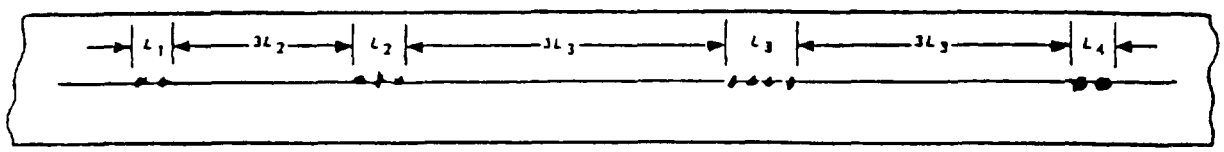


Figure 7.11(a) : Aligned rounded indications.

The sum of the group lengths shall be less than t in a length of 12 t.

Maximum Group Length	**Minimum Group Spacing**
L = ¼ in (6.35 mm) for t less than ¾ in (19 mm) L = 1/3 t for t equal to ¾ in. (19 mm) to 2 ¼ in. (57 mm). L = ¾ in. (19 mm). for t greater than 2 ¼ in. (57 mm).	3 L where L is the length of the longest adjacent group being evaluated.

Figure 7.11(b) : Groups of aligned rounded indications.

(1) The height of the peak signal.

(2) The defect length, as measured by the length of probe movement parallel to the weld producing an indication greater than a specified amplitude.

(3) The extent of probe movement perpendicular to the weld which produces an indication: this length of movement can be translated into a through-thickness dimension.

(4) The number of defect indications per unit length, or unit volume of weld.

If the operator can distinguish between defect and non-defect indications, and can identify the nature of some defects either from their location, or from local probe movement (e.g. rotation), the above four criteria can be used to produce acceptance data. Figure 7.12 indicates the philosophy proposed.

The ultrasonic equipment is calibrated and the evaluation and rejection thresholds AA 'and BB' are set according to agreed criteria. When a defect is found, and proved to be real, the probe is adjusted for maximum signal. If the amplitude is below BB', the defect is accepted; if it is above AA' , the defect is recorded as rejectable. If the amplitude is between AA' and BB', the defect is examined in more detail to decide whether it is cracklike; it is checked for length, or number/unit length and compared with agreed criteria. Line CC' is the amplitude reference level established by reference to standard reflectors, such as side-drilled holes or flat-bottomed holes.

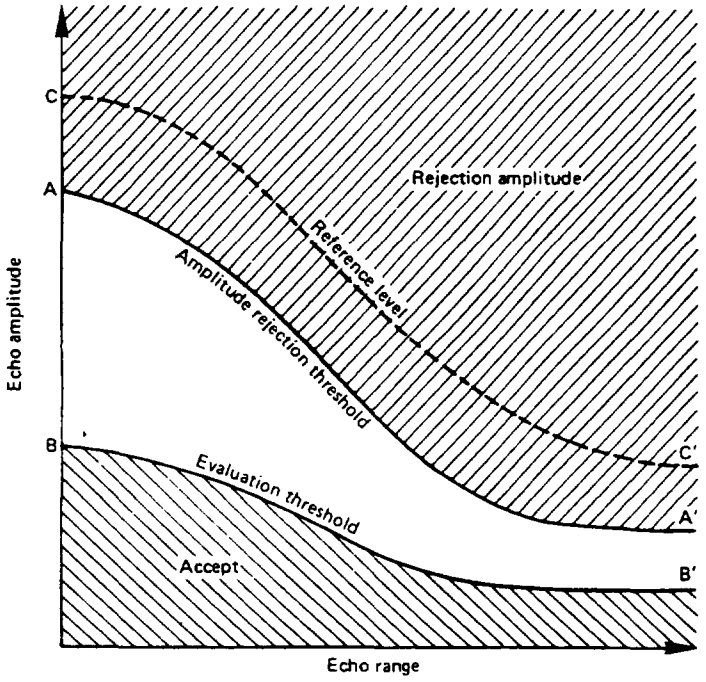


Figure 7.12 : Principles of a proposed acceptance standard for ultrasonic weld testing based on quality control criteria. The curves are determined for specific applications.

In fitness-for-purpose examinations, a similar procedure has been proposed, but with more emphasis on measuring defect size, by starting with a higher sensitivity (e.g. 'grass' just visible), more detailed scanning over any defect found, and dimensioning by means of a DGS diagram, or echodynamic evaluation.

A proposed acceptance criteria for the three classes of work is shown in Table 7.3 for manual ultrasonic inspection, for longitudinal weld defects. If there are more than four measurable defects in a length equal to four times the wall thickness, the sensitivity should be increased by 4 dB and the inspection repeated. These proposals for an ultrasonic inspection standard also cover the extent of the inspection, the number of probe angles to be used, the surface condition, and a guide to defect characterisation into four types of echodynamic pattern.

An alternative simpler approach to specifying acceptance standards for ultrasonic weld inspection is simply to state that no defects which occupy more than a specific percentage of the weld thickness shall be acceptable: for example, 20% of the nominal thickness for stringent applications, or 30% for moderately-stressed applications. Such an approach has been proposed in ISO draft DP 5817 but such simplification is in effect ignoring a lot of data which the ultrasonic signal contains and should be supplemented by the criteria for individual types of defect as detailed above for a radiographic acceptance standard.

TABLE 7.4 : IIW PROPOSALS FOR DEFECT ACCEPTANCE BY ULTRASONIC EXAMINATION

	Class, thickness range (mm)		
Quantity	I, 7 - 50	II, 7 - 100	III, 7 - 300
Evaluation threshold	DAC + 10 dB (33% DAC)	DAC + 14 dB (20% DAC)	DAC + 14 dB (20% DAC)
Amplitude rejection level	DAC	DAC + 4 dB (65% DAC)	DAC + 4 dB (65% DAC)
Length evaluation level	DAC + 10 dB	DAC + 10 dB	DAC + 10 dB
Maximum acceptable length (if above length evaluation level)	Wall thickness	75% wall thickness	50% wall thickness

Notes:

DAC — distance-amplitude correction value for the distance of the echo from the probe. The DAC curve is established with 3 mm diameter drilled holes. (DAC + 10 dB) means a level 10 dB more sensitive than a 3 mm cylindrical hole at the range of the defect.

It is worth noting that data handling techniques are developing so rapidly in ultrasonic testing that these acceptance criteria might eventually have to be reformulated in a digital data format to enable the acceptable sizes of defects to be built into a pattern-recognition programme.

7.4 FLAW EVALUATION BY FRACTURE MECHANICS

Retirement for cause (RFC) or fitness for purpose are life-cycle management procedures. The RFC procedure enables full use of the safe life inherent in each component, as opposed to arbitrary retirement from service of the component at a calculated low-cycle fatigue life. Clearly, the high frequency and cost of removing the components from service are dominant. The most obvious method of reducing overall costs is to reduce the frequency of component failure. This can be accomplished by improved raw material, NDT and process control. The RFC approach is based on fracture mechanics methodology and quantitative NDT whereby components are inspected and, if unflawed, returned to service. The return-to-service interval is determined by a fracture mechanics calculation of critical crack size as well as the crack growth rate. If the crack exceeds the detection threshold, the component is retired from service; if the crack is less than the detection threshold, the component is returned to service. This procedure is repeated until a crack of the critical or greater size is detected, at which time the component is retired.

When a defect is detected by non-destructive testing, it becomes a matter of importance to evaluate it in relation to the strength of the material in which the defect is detected. This evaluation can be made by utilizing the fracture mechanics analysis (Section 5.4). In doing so, however, there are several important factors which must be taken into consideration. The most important among them are the reliability of non-destructive test results, reliability of information of external forces or stresses imposed on the structural segment and the reliability of material strength.

Some of the concepts utilized in making fracture mechanics analysis are briefly given here. Firstly it is assumed that a crack or a crack-like defect exists in the structure. The essence of the method then is to relate the stress field developed in the vicinity of the crack tip to the applied nominal stress on the structure, the material properties and the size of the defect necessary to cause failure. The elastic stress in the near vicinity of a crack tip is called stress intensity factor and is denoted by K_I. The critical value of K_I at which crack instability occurs is denoted by K_{IC}. The relationship between K_I and the applied stress is given by

$$K_I = C\sigma (\pi a)^{1/2}$$

where

- C = a constant dependent upon the crack geometry and the component geometry
- a = crack size
- σ = nominal service stress

Values of C are available in various text books and handbooks. Fracture occurs when

$$K_I > K_{IC}$$

Other important definitions are K_{ISCC} which is the threshold level of K_I below which stress corrosion cracking will not occur which is a constant for a given material and environment. Crack growth rate as a function of ΔK_I under cyclic loading is given by da/dN while da/dt is the crack growth rate as a function of K_I under sustained loading. ΔK_{Ith} is the threshold level of ΔK for fatigue crack growth.

In another approach of fracture mechanics, specially applicable to very tough materials, a term "crack-opening displacement (COD)" similar to K_I is defined. This is based on the idea that cracks advance when the strain ahead of the crack reaches some material critical value, for which there is a corresponding material critical value of crack-opening displacement. This is denoted by δ and, as with K_I, can be calculated as a function of service stress, crack size and geometry. This can then be compared with the critical value of COD for a given material to determine whether or not crack extension will occur. Crack extension occurs when $\delta > \delta_c$.

A parameter called J integral has been defined and may be thought of as an intensity parameter for an elasticplastic stress field or strain field ahead of the crack tip. The K factor is applicable only for an elastic stress field ahead of the crack tip while J parameter is applicable for very ductile materials which develop a large plastic zone ahead of the crack tip. J may be calculated for various combinations of stress and crack size and shape. This can be compared with the material critical value of J, namely J_{IC}, to determine whether or not crack extension will occur. As for other relationships, fracture occurs when $J_I > J_{IC}$.

The various factors K_I, δ and J_I are given as functions of service stress, flaw size and flaw shape in various text books and handbooks, for example, references 9 and 18 in the bibliography.

It is clear that how large a crack is allowable is determined on the correlation between the existing strength of the defective material and the design stress. It cannot be generally stated that a crack up to a certain size is always permissible. In some cases, allowable crack size for structural segments of machinery is determined at the design stress. A design concept of permissible damage has been introduced into the aircraft sector. The idea is to perform careful quality control and inspection during manufacturing of the aircraft, and after it is activated, scheduled periodic in-service inspections.

Permissible size of an initial defect or a defect detected at the in-service inspection is specified in accordance with the duration of service expected before the next scheduled inspection. In this way a harmful flaw in the material, tool marks or drill holes, does not develop into a crack of a size which may reduce the safety or impair the performance of the aircraft; thus the required remaining strength is maintained. Two different methods are employed :

One of these is called "design of slow crack propagation". The design is made in such a manner that an initial flaw if any, may propagate, but does not develop to a size which may cause structural failure during a designated span of time. The size of flaw permitted is determined on the basis that the required remaining strength is maintained for a period twice as long as the life of the aircraft for inaccessible locations where an initial flaw cannot be inspected, and for a period twice as long as the interval of periodic inspections for accessible locations where defects can be inspected during service.

With the other method, "Fail-safe design", the design is made such that rupture of a single segment does not impair the overall safety, or crack arrestors are placed at appropriate locations so that propagation of a crack is checked and prevented.

As an example we may consider the case of military aircraft in the USA on which typical crack sizes of the order of 0.1 to 5 mm are assumed to exist in various locations. Safety analyses must be made on the assumption that these flaws exist from the beginning. If a design should be made assuming initial flaws smaller than those indicated the technical ability of inspection must be demonstrated to prove that 90% or more of the flaws exceeding the specified sizes can be detected with 95% reliability.

ASME boiler and pressure vessel code and other standards have used the fracture mechanics approach criteria. There are numerous examples of where companies have employed the overall technology to good advantage. These encompass a broad area of materials and applications ranging from the very heavy electrical power-generation equipment involved in turbines, generators, nuclear power plants, etc., to small low-cost, high-volume components in consumer products. Similarly the purpose for which the technology has been employed is also broad; some of the major areas involve the establishment of realistic inspection standards and corresponding non-destructive procedures; life expectancy and structural reliability analyses of hardware suspected or known to contain cracks or crack-like defects; failure analyses and definition of required corrective actions analyses of effects of postulated accident conditions on structural integrity; failure probability analyses and various other purposes.

While the technology has been employed gainfully for many purposes, the primary intended use of the technology is to prevent structural failures and, at the same time, promote more effective designs and more efficient use of materials. Herein lies the singular, most significant contribution which the technology can make. There are also areas in which there is still much opportunity for improvements and refinements.

One of these areas is obviously NDT. While in many situations the present state of the art in NDT is quite adequate, there are some specific areas where enhanced non-destructive capability is desired and needed, or where advanced non-destructive concept could improve the overall value of this systems-type approach substantially to ensuring structural reliability.

There is a recognized need for the development of industry-wide standards for calibrating and using non-destructive systems. Many of the existing standards are

unique to a given industry or fraction within an industry. While the in-house standards developed for specific situations may be perfectly adequate, the lack of common standards can lead to difficulties in comparison of results between individual companies or producers and suppliers. The lack of reproducibility of NDT results between various non-destructive techniques or inspection teams has been demonstrated dramatically by several interlaboratory programmes.

In some critical high stressed applications where relatively high-strength and brittle materials are required, the sizes of defects of concern can be quite small. This is especially true for those situations where relatively low values of applied K or ΔK are involved. For example, a notched member with a high stress concentration and a low $K_{ISCC}$for the available material and the service environment. In this case the defect size that would develop an applied K level in excess of K_{ISCC}(and hence endanger reliability due to stress corrosion accelerated crack growth) could be in the order of 0.25 to 0.5 mm in depth. Another example where small defects are of concern is those applications where extremely long cyclic life ($\approx 10^9$ to 10^{12} cycles) is required and one must be concerned with keeping ΔK (the combined defect size and stress, $\Delta K \approx \Delta a(\pi a)^{1/2}$) below the threshold for fatigue crack propagation. In such cases, the ability of NDT to locate and define small defects is paramount to ensuring the desired reliability.

One of the more serious current limitations is associated with the inability of present NDT to differentiate between types or to describe the detailed makeup of "clusters" or clouds" (clusters or clouds composed of many small defects) indications. Such types of defects are of particular concern in heavy section applications such as large steel forgings and welded structures where clusters or clouds are inherent in the steel making or fabrication processes. In large forgings these may be fine non-metallic inclusions, microcracks, or voids from the original large ingots involved. In heavy section welds the clouds could be fine porosity, entrapment of foreign material such as slag or fine microcracks. At present, NDT in most cases will be capable of defining the location and general dimensions of the cloud. A fracture mechanics analysis will consist then of drawing an envelope around the cloud and treating it as one large single defect, such as specified in ASME boiler and pressure vessel code. In most cases (especially for clouds of fine non-metallic inclusions in large forgings) this is a very conservative approach. The life prediction based on assuming a single large continuous flaw is only a small fraction of the actual life of the component. Most of the actual life is spent in the process of initiating cracks within the cluster or cloud and in the subsequent joining up of a network of cracks to form a single continuous defect. While it is currently possible to analyse this initiation and link-up process from an analytical or experimental testing view point, it is not possible to relate these results to NDT. Hence this part of the safe life of the component and structure cannot be utilized in any quantitative fashion. Improvements in NDT which would differentiate between harmful and innoculous types of cluster or clouds would be very beneficial. Further refinements in NDT which would describe the detailed makeup of the specific types of clouds (so that the interaction between neighbouring flaws could be analysed and the link-up process could be monitored by NDT during service) would represent a dramatic technical breakthrough in improved life-prediction methodology. Hence this is a very fertile area for NDT technology development, e.g. focused transducers and acoustic holography.

Considerable effort and interest is being devoted to the use of acoustic emission as an NDT tool, especially for in-service monitoring of critical structures or components. From a fracture mechanics or structural reliability analysis point of view, the ultimate development of this NDT tool has tremendous potential. For example, if in the future it becomes possible to establish precise, quantitative correlations between some acoustic emission signature for a crack in a structure and the K or ΔK level prevailing in the region of the crack, one can then use the acoustic emission for the precise location of that specific point in time in the failure process, and the remaining life of the structure can be evaluated using the fracture mechanics approaches. Continued surveillance via acoustic emission could be used to follow the sequence of failure and ultimately to define safe limits. The key to the potential exploitation of this approach is the development of reproducible, reliable, quantitative correlations between acoustic emission and the applied K in the structure. This is another fertile area for some good collaborative development work between NDT (acoustic emission) and fracture mechanics disciplines.

7.5 NDT REPORTS AND RECORDS

7.5.1 The test report

The final outcome of a non-destructive test is the test report. It is mostly on the basis of this report that all decisions regarding the further treatment of the defects found by testing and the fate of the tested part are to be made. How far are the reported results reliable and if they are not reliable can the operator be asked to recheck and reconfirm the earlier findings? In other words are the reported results reproducible, and how far has the report helped in the reproducibility of results? In view of these and many other requirements it is essential that the NDT test reports are prepared with utmost care. In many cases reports are the only means of knowing the processes involved in the manufacture of the components and the state of their soundness at the time of installation. This information is specially quite valuable while investigating some premature failures. The reports are thoroughly scrutinized and analysed by the inspection and audit agencies and form an indispensable requirement for quality assurance.

The essential requirements of a good NDT report can be said to be its unambiguity and reproducibility. Therefore while preparing a format for a report all the variable factors that affect the sensitivity of flaw detection for a particular NDT method should be kept in view (Section 6.1.1). In fact, in principle, the values of all these variable parameters should be fixed and noted in the report form. It should be thoroughly considered whether all the desired information has been given in the report such that using the report it would be possible to reconstruct the exact conditions of the test in case a repetition of the results is required or would the report help in exactly locating the defective areas in the tested parts in case repairs were to be undertaken? We will elaborate these points with an example from radiography and the reports for other NDT methods can then be developed along similar lines.

The details of the type of specimen, its thickness, geometry and shape and the portion being radiographed should be recorded in the report form. A unique identification number should be allotted to each exposure and this should appear on the radiograph, on the test specimen and in the report. Preferably this number should be linked to the design drawing number. It is only with the help of this identification number that parts can be rejected or repaired or repeat inspections made if desirable.

Applicable procedure which itself should have an independent number should be referred to in the report.

Exposure conditions such as kilovoltage, milliamperage, source-to-film distance, object-to-film distance, source size and type and make of the equipment, and the type of filters used, if any, and number of image quality indicators should be given.

Type of film used, the conditions of development (time and temperature), fixing and washing, the strength and type of various solutions should be given.

The sensitivity of IQI achieved and the density of the radiographs obtained should be mentioned.

Film viewing and lighting conditions constitute an important factor and some mention of these should preferably be made.

The accept/reject criteria and the applicable procedure/standard for this should be mentioned. The defects should be identified in terms of their nature, size and location. If many radiographs have been taken under same conditions the results may be tabulated according to the identification numbers of radiographs.

The name of the organization conducting the radiographic testing should be given in the report and the personnel carrying out the radiographic work should give their names and levels of valid certification. The report should be signed by at least one level- 2 person who may be in charge of the radiographic work. If possible the signatures of a more responsible officer of the department should also be taken.

The name of the client and other possible recipients of the report should be listed on the report.

Finally the report should be dated and should have a unique identification number of its own. Two of the typical forms for radiographic test report are given in Figure 7.13 (a) and (b).

7.5.2 Other records

In addition to the test report there are some more documents which form an important part of the non-destructive testing process. These are also directly linked to the test report and are always needed whenever the report is to be verified or the tests are to be repeated or for the purposes of quality audits. These records form an important requirement of the quality assurance programme of the organization, and are a means to traceability.

ORGANIZATION	RADIOGRAPHIC INSPECTION REPORT	REPORT No.: Page: of
Customer:	Object:	Job No.:
Material:	Manufacturing Process	Drawing No.:
Specification/standard:	Procedure No.:	Mapping No.:

TECHNICAL INSPECTION DATA

File Location Plan No.:	X ray Equipment Manufacturer and Type::
Radiation Source:	Source/Focal Spot Size:
Quality Level:	Film Brand, Type and Size:
Exposure Technique:	Screen Material and Thickness: Front (mm) Back:

Part No.	File Identification	Section Thickness mm	Outside Diameter mm	Tube Voltage KV	Tube Current mA	Activity Ci	Exposure Time min	Source to Object Distance mm	Image Quality Indicator		Remarks
									Position	Sensitivity	

	Signature:
	Name of Inspector:
	Place:
Extend of Inspection	Date:

Figure 7.13 (a) : A typical example of a radiographic test report form.

The written and numbered procedure for executing the non-destructive tests should be present in the organization's records as well as with the persons doing the job. A procedure should include as a minimum the following sections:

(i) Procedure identification number and the date it was written.

(ii) Scope.

(iii) Applicable documents.

(iv) Personnel.

(v) Equipment/calibration/reference standards.

(vi) Identification and type of test object to which the procedure applies.

(vii) Test method.

(viii)Reporting levels/examinations.

(ix) Acceptance criteria.

(x) Marking plan for the test object.

(xi) Reporting.

ORGANIZATION	**RADIOGRAPHIC REPORT**	REPORT No.:
		Page:

CUSTOMER:	CONTRACT No.:
JOB No.:	PLACE:

SOURCE TYPE/No./ACTIVITY:	TECHNIQUE:

FILM TYPES/SIZES:	QUALITY STD:	MAPPING No.:

PROCEDURE No.:	RP PROC. No.:	EQUIPMENT No.:	DRAWING No.:

RESULTS

Weld No./Part No.	Radiograph No. or Position	Density	Radiographic Quality A/R	Material Quality A/R	Type of Defect	Position of Defect

LEGEND: A: ACCEPT C : CRACK R: REJECT U : UNDERCUT	APPROVAL
P: POROSITY SC : SHRINKAGE CAVITY SI: SLAG INCLUSION AR : ARTIFACTS(SPECIFY)	CLIENT : AUTHORIZED INSPECTOR DATE:
LF: LACK OF FUSION II : INCORRECT IQI IP: INCOMPLETE PENETRATION	CERTIFICATION:

Figure 7.13 (b) : A typical example of a radiographic report form.

A written record of the calibration of the test equipment should be maintained. In case the equipment needs periodic calibration the dates of present and next calibrations should be identified. If the calibration has been carried out or checked by a specialist agency, its name should be mentioned.

A documentary record of the qualifications and certification of all the persons involved in doing NDT and writing and signing reports should be available and should be producible on demand. The dates when the validation of certificates becomes due should be mentioned and properly dated certificates of eyes tests of all the operators should be maintained. Evidence should also be maintained on the training received and the education and work experience attained by operators. In fact it would be ideal if a mandatory log book for all the NDT personnel is maintained.

In brief, written documentation is the best way to traceability, reproducibility and ultimate reliability of the tests and consequently the tested parts. In the case of NDT working procedures, this will mean a comprehensive procedure written by a competent (suitably qualified) person, and an inspection carried out by a suitably qualified operator reported accurately on an inspection report form.

8. TRAINING, QUALIFICATION AND CERTIFICATION OF NDT PERSONNEL

8.1 IMPORTANCE OF PROPER TRAINING AND CERTIFICATION

Looking at the numerous variable factors influencing the sensitivity and quality of non-destructive testing, the factor common to all the NDT methods is the operator, the person responsible for executing the tests and reporting the results (Sections 6.1.1 and 7.1). The traits thought essential for this person are listed to be his eyesight, qualifications and experience. The qualifications can easily mean the academic competence and knowledge and the type of training he has received. It is through the operator that the results of NDT tests are compiled for further consideration and decision about the fate of the tested part. In many cases he himself holds the responsibility of passing a judgement on the acceptance or rejection of the part. It is the operator through whom the results of NDT can be falsified. If the operator is not properly knowledgeable, trained and experienced he might totally misjudge the results of NDT and reject the parts which are sound and capable of performing in the service. On the other hand he might send the faulty parts into service which may become a source of premature failure. In both the cases the consequences are going to be adverse. In the first case the organization is going to suffer undue production losses while in the second the premature failure may lead to even bigger losses. Of no less importance is the integrity of the operator in view of his ability to falsify the results intentionally.

Non-destructive testing, in radiography, uses hazardous radiation sources. There is a danger of undue radiation exposures to the radiographers as well as to the general public if the radiographer is either ignorant or careless about these hazards. It is

estimated that industrial radiography accounts for more than 50% of the overexposure greater than 5 rem (50 mSv) to the whole body or 75 rem (750 mSv) to the extremities. It is therefore essential to properly train all the radiographers in the use of radiations, and the radiation monitoring and handling equipment. All such persons should be properly certified and such certificates in fact should be cancelled in case their holders are found to be indulging in any malpractices or negligence regarding the safe use of radiation sources.

NDT is a mandatory science for the complex industrial systems expanding in our world today. This increase in industrial systems and related NDT needs has come principally because of accelerated costs for systems maintenance, replacement, and quality and safety requirements. Engineers, scientists, and management have been forced to find very sophisticated ways to diagnose system operational problems, to predict the remaining life of systems, to help design replacement or refurbished systems, and then to build the systems safely and put them into operation. Each step of this scenario requires quality-control of NDT procedures and applications. Recognizing that NDT expertise is a key resource for the current and future needs of industry, industrialists are becoming more aware and concerned that such expertise is not taught to every undergraduate science and engineering student. These same individuals in industry perceive that it is not just the technical discipline of NDT that is missing; it is the whole philosophy of NDT , which must become a part of the new engineering curriculum. This then brings out the need for making NDT a part of the entire educational programme in addition to training the operators for specific jobs.

For engineers, the simple fact is that outer and inner space have challenged the human mind and required us to change our engineering to meet the challenge. With the advent of new space-age materials, engineers will be able to pursue structures and systems that require lower weight, greater strength, higher performance, less maintenance, and greater reliability to meet the competitive and social challenges of the future.

Flaws that were once acceptable, for example, to aircraft component designs are no longer acceptable in aerospace components. Now a necessary part of the original design of a component is the need to provide a meaningful NDE approach to the inspection of a system once it is in-service. Extended life of large expensive systems is the current trend and will intensify, not diminish. We are redesigning, modifying, adding, and changing to meet industry's needs. All of these factors will influence the education process to some degree.

Over the years, the effective application of NDT has been controlled by the combination of adequate inspection procedures, appropriate and functioning equipment, and competent personnel. The last requirement applies not only to those who conduct a test but also who interpret and this aspect is often neglected, for those responsible for designing, planning, supervising, and reporting/evaluating NDT. The three conditions have been effectively fulfilled for some time in the aerospace industry, where NDT has contributed significantly to the success of safe air travel. Through a combined effort of manufacturer and operators of aeroplanes, government agencies, engineers, and scientists, a remarkable safety record has been

achieved in a very competitive market. It was in this market segment that, among other things, qualification of NDT practitioners was dealt with systematically for the first time.

8.2 INTERNATIONAL TRAINING AND CERTIFICATION

The NDT community has been conscious of this very important aspect of the technology and almost simultaneous with the development of NDT the training and certification of NDT personnel has been given due attention. Thus in the developed countries where NDT is being extensively practised, there is a sound network of places and institutions for imparting training to the NDT personnel.

There are a number of approaches to achieve the training and certification. Best known is the approach used by General Dynamics (GD), similar to the later recommendations in ASNT Recommended Practice No.SNT-TC-1A. It seems that the GD approach worked at a time in the aerospace sector when there was open communication between all involved in safety matters. NDT became a part of the design, and many identical units enabled the circulation of detailed procedures for NDT together with the maintenance instructions.

The GD/ASNT personnel qualification procedure is based on an examination procedure by the employer, with three levels per NDT method. Qualification comprised minimum NDT training hours in relation with basic education, a minimum period of experience, a good physical condition, and passing of an examination. The qualification is followed by employer certification, which described the person's suitability for a (specific) job in view of liability.

In many other engineering fields, with less open communication between authorities, manufacturers, and operators, the GD/ASNT approach became popular but was regularly misused. Insufficient supervision and lack of interest in a decent inspection deteriorated the system. Moreover, this employer-based system also became popular for market protection.

Besides this pragmatic aerospace approach, two important other qualification systems can be recognized. On the basis of the welder's qualification, the welding community promoted a one-level, very fragmented, specific weld- inspection scheme later extended to other engineering areas. The object configuration was the main parameter. The best known example is the CSWIP scheme applied in the UK. This very detailed system led to scarcity of ultrasonic inspectors.

A completely different approach, based on extension of professional education, has been to provide NDT personnel with a solidly theoretical and practical general education but without an emphasis on specific knowledge and skills. A good example is the approach of the Deutsche Gesellschaft fur Zerstorungsfreie Prüfung (DGZfP)-the German Society for Non-destructive Testing. The DGZfP system is, however, more appreciated by scientists than by industry. This approach, no doubt, is the best way to accommodate new developments and offer a prestigious

profession with a career structure. However, because the short-term demands of industrial projects often overrule long-term vision, there is not a bright future for this system either.

There are a number of ways in which education, training and certification is provided in the field of NDT. It is taught in many universities of the developed countries mainly as a part of other disciplines of education curriculum such as physics, electrical engineering, welding engineering, mechanical engineering, materials science and quality control. It also makes a part of the programmes of colleges and vocational training schools. There are a few institutions in the USA and UK which have exclusive degree programmes in NDT.

The training of the NDT practitioners who are actually supposed to perform NDT on the job is specially organized very carefully. This is mostly being done either by private NDT schools or institutions run by or in collaboration with professional NDT societies. These places have well qualified and experienced NDT trainers and a good collection of NDT test pieces with known defects. Their clear objective is to prepare the personnel for certification examinations which are separately organized. Materials Evaluation (volume 45, No. 2) a publication of American Society for NDT has published a directory of such training institutions.

The certification of NDT personnel is mostly being either done by the professional societies in various countries or by the regulatory or technical education bodies. A list of the well known NDT societies and institutes has been given in Section 9.8. Each country has a national standard on the subject of training and certification of NDT personnel laying down the requirements of basic education and experience of the persons intending to take certification examinations. These standards also contain the procedure for conducting certification examinations and the responsibilities of various persons. The type and validity of the certificate are also included. Some of such standards are listed in Section 6.3.4.

8.3 IAEA EXPERIENCE

From 1967 to 1974, the Organization of American States (OAS) had been sponsoring fellowships through its Multinational Metallurgy Programme, and NDT formed a part of these and later similar courses. Students attending these OAS programmes from throughout Latin America, thus exposed to the technology and application of NDT, returned to their own countries and began asking the UN agencies including the IAEA for assistance in NDT. IAEA spent two years evaluating the need for a regional project. In 1982, with the support of UNDP, IAEA, the United Nations Financing System for Science and Technology for Development (UNFSSTD), and the United Nations Industrial Development Organization (UNIDO), six countries started the Regional Non-Destructive Testing Project for Latin America and the Caribbean. By 1985, an additional eleven countries had joined, and three countries, Italy, Canada, and Germany, had become active donors of equipment, expertise and funds.

While the sponsoring agencies and donor countries were contributing expertise, travel funds and equipment, it was also recognized by all that there needed to be a

yardstick by which to measure the adequacy of the training, and that this training had to be harmonized within the region. A regional working group on training and qualification was established, composed of one representative from each country in the region, selected for his experience, knowledge and competence in NDT. This group addressed the issues of regional guidelines for training and qualification, developing a draft regional standard for qualification and certification of personnel based on the existing Argentine standard, and a set of training guidelines for three levels in each of the five basic methods.

In early 1984, IAEA convened a meeting of international experts in Vancouver, and asked their advice on the status of international harmonization. Following the recommendations of this meeting, IAEA decided to support the work of ISO/TC135/SC7 and to recommend its draft for use in all IAEA projects, closely monitoring developments and keeping open the option of developing its own document if progress appeared to be too slow. As another result of this meeting, the IAEA became an active member of ISO/ TC135/SC7 and contributed strongly to its work.

In the Latin America and Caribbean region, the participating countries then agreed to use the latest version of the ISO draft as a model for the national standards being processed through their respective approval systems. The countries in the Asia and Pacific regional project also agreed and, along with donor countries of Japan and Australia, began the process of harmonizing their respective national standards to the ISO model. As a particular contribution, the Latin America and Caribbean Regional Working Group's Training Guidelines were published by IAEA and included by reference in the ISO Draft Proposal.

A subsequent review of progress by IAEA's group of consultants in May 1986 resulted in a recommendation that the IAEA and its member countries should continue to support the ISO developments, using the latest revision of the draft standard as the basis to establish national qualification and certification schemes.

Because of the Latin American project, there had been some 18 000 participants in training courses either directly sponsored by the project or held within the participating countries following the project's guidelines. Through the careful selection of qualified candidates for regional courses, and paying particular attention to developing trainers, the project reached the point where all but a few of the seventeen participating countries were self-sufficient to the point of meeting their own needs for courses in the five basic methods up to and including level 2. Most of the seventeen had national NDI societies, and had promulgated national standards for the qualification and certification of NDT personnel.

Encouraged by the results of the project in Latin America and the Caribbean, IAEA in 1981 incorporated an NDT sub-project in its Regional Co-operation Agreement (RCA) for Asia and the Pacific which was looking at a much wider field of radiation technology which included radiotracers, radiation processing and nucleonic control systems. Seventeen countries of the region are members of the agreement while Japan and Australia are the donor countries. By the end of 1995 large number of trainees have been trained as a result of the project. This training is imparted following the syllabi guidelines of IAEA-TECDOC-628 and the text

books developed under the project. Fifteen of the countries have established the national certifying bodies in accordance with the requirements of ISO 9712 or equivalent technical training boards. Fourteen have formed the professional NDT societies which are considered to be an essential organ for looking after the needs of NDT in each country even after the project is over. A third project along similar lines has recently been started for the North African and Arab countries. Thus the role of IAEA in promoting NDT around the world, in issuance of a unified standard for training and certification and for making efforts for international harmonization in certification and consequent applications of NDT has been remarkable.

8.4 QUALIFICATION TO ISO STANDARD

The background and the need for having a unanimously accepted standard for qualification and certification of NDT personnel at the international level is explained in Section 8.5. Such a standard has, in fact, been issued by the International Organization for Standardization (ISO) and is designated as ISO 9712, Non-destructive testing - Qualification and certification of personnel. In view of its importance the full text of the standard is included as Annex-I. Salient features of the standard are, however, outlined in this section.

ISO 9712 emphasises the central certification for each country supervised and controlled by a national certifying body (NCB) which should be constituted such as to have representatives from all interests related to NDT. It makes formal training as a pre-requisite for seeking certification and sets the minimum training hours needed for this purpose. It recommends the syllabi which may be followed for these formal training courses. It establishes the experience needed to qualify for certification. The methods for conducting certification examinations and the type and minimum number of questions to be asked are laid down. The method of marking the papers, weight and pass percentages required for obtaining certification are laid down. It recommends three levels of certification, level-3 being the highest and defines responsibilities for each level. The type and validity of certificates is fixed and so is the procedure for their renewal. The requirements of sound physical fitness specially the eyesight have been included. Finally the standard lays down requirements for keeping proper records of the certified personnel.

8.5 INTERNATIONAL HARMONIZATION

The system of all the countries having their independent certification standards presents certain problems at the international level especially in the case of multi-national companies who most of the times insist on having the NDT personnel qualified to their own standards instead of accepting the certification standards of the host countries. This is neither beneficial to the companies nor to the host countries. Had the standards of training and certification been uniform this problem would have been resolved. Varied certifications also present a problem to the movement of the NDT personnel from one country to another while this is not so for many other professions. But whenever such a move has to be made the NDT person has to obtain multiple approvals from different countries. The difference in certification standards sometimes leads to difficulties in reaching bilateral or international agreements thus presenting trade barriers.

The NDT community was quite aware of the problems and a concern was shown at every international gathering of the community members. In the early 1970s it was realized that the forces of rapidly advancing inspection technology and increasingly demanding test reliability are making the requirement for harmonized qualification and certification schemes a particularly urgent need for every country which has an industrial base, no matter how small.

The International Committee on Non-destructive Testing (ICNDT), at its meeting in Warsaw in 1973, recognized the need for international harmonization in training, qualification and certification and formed a working group whose objective was to develop proposals for such harmonization. Between 1973 and ICNDT's meeting in Melbourne in 1979, this working group attempted to critically review and compare national systems. A long discussion in Melbourne resulted in a new approach agreement upon some common basic rules followed by development of detailed syllabi for each method. These basic rules were as follows:

1. Training and qualification according to test method.
2. Training and qualification divided into three levels.
3. Definition of minimum knowledge and skills.
4. Qualifying examinations to be carried out by a neutral and independent body.

At the time of the 10th World Conference on NDT in Moscow in 1982, ICNDT's Working Group submitted a recommended syllabus for ultrasonic testing and reported on parallel and co-ordinated activities within the European Working Group for Harmonization of Training and Qualification of NDT Personnel.

On the basis of the work of a combined international and European work group, ICNDT eventually adopted the following principles in Moscow in 1982.

(1) (a) Basic training and qualification of NDT personnel will be related to the testing methods.
   (b) Training and qualification be divided into three levels.
   (c) According to qualification requirements, the necessary knowledge and skills to be demonstrated will be harmonized and defined on a world-wide basis.
   (d) Qualification examinations are to be carried out in the different countries by neutral (independent) organizations.

(2) Agreement on mutual recognition of the essential objective of qualification is an effective means of international co-operation.

On the basis of these guidelines, an ICNDT work group started to compose the minimum requirements for the "general theoretical" part for six methods. It became clear that there was also a need for formulating in more detail the common denominator of the qualification procedure. This led to a document on Basic Requirements for National Personnel Qualification and Certification Schemes. In essence, this document defines various terms and formulates guidelines, such as examination independent of employer and trainer (training institute) and under supervision of a national non-profit, independent body, a theoretical and practical hands-on examination for all levels; and a possibility of performing additional job-specific examinations. These "minimum" requirements and "basic" requirements

were adopted by ICNDT at the World Conference for Non-destructive Testing, Las Vegas, November 1985.

In the meantime, Canada in 1980 became the secretariat of ISO/TC- 135/SC-7 on the qualification of NDT personnel. This subcommittee first convened in Sept. 1983 in Ottawa. A second meeting took place in February 1985 in Paris, where various systems were compared and common aspects were determined. At this meeting, a small work group was formed, which, with the input of ICNDT, IAEA and many other organizations came up with a draft of an ISO standard very much along the lines formulated within ICNDT. With only minor modifications, the daft obtained great support in the subcommittee meeting in Milan, May 1986. At the last meeting of the SC7 held in Philadelphia in November 1987 the draft proposal was reviewed and it became apparent that the draft had the support of a substantial majority of the SC7's voting members which numbered at 26. Unanimity of views among members was at last achieved in 1989 at the Berlin meeting and the draft was submitted to ISO. After that the formal procedure of ISO for issuance of standards was followed and a standard "ISO 9712 : Non-destructive testing - Qualification and certification of personnel" has been issued. It is hoped that the ISO standard will play an important role for an harmonized training and certification of NDT personnel throughout the world consequently ensuring a uniformity in the non-destructive testing practices and the quality of the tested products. However, issuance of a standard by ISO is not the ultimate in assuring international harmonization; it is the beginning. It has to be seen how faithfully and honestly the standard is practically implemented by each country. In this regard following steps are proposed as a means to ensuring the achievement of harmonization :

(a) There should be well defined syllabi for various levels of certification, firstly in the basic six NDT methods as listed in ISO 9712 and then for the additional methods such as leak testing, acoustic emission, neutron radiography, etc. This has been done by the IAEA in two of its TECDOC publications. The first was IAEA-TECDOC-407 which included syllabi for liquid penetrant testing, magnetic particle testing, eddy current testing, radiographic testing and ultrasonic testing and the latter and revised is IAEA-TECDOC-628 which includes additional methods of visual testing and leak testing.

    There is no doubt that IAEA-TECDOC-628 is not an ideal document and there is a room for improvement, but it is quite a satisfactory document if it is treated as containing the minimum syllabi requirement for fulfilling the needs of ISO 9712. In view of rapid developments that are taking place in the field of technology and also the commensurate testing methods, it would be appropriate if a revision of the syllabi is made every five years.

(b) Following the syllabi development of training materials, text books are the next important steps which need to be developed. IAEA has started to work in this area as well. As a first step the text book on radiographic testing method has been issued which follows the syllabus of IAEA-TECDOC-628 and can be used for training of radiographers at all the three levels. The text books for the other methods are also proposed to be similarly developed. Related to these it would be appropriate if the books are updated following the revision of syllabi every five years. Also at some stage the IAEA may send them for comments to

various well known certification bodies around the world such as those in the USA, Canada, the UK, France, Germany, Italy, Japan, Australia and China with a view to achieving a uniformity in the teaching materials.

(c) The next important step for achieving harmonization is a uniformity in the content of practical work aimed at various levels of certification as well as a uniformity in the standard test pieces containing known defects which are used for training and examinations for certification. IAEA-TECDOC-628 contains some guidelines about the practical content of various training courses for different levels and different NDT methods. Guidelines were also provided about the practicals' content and the procedure for conducting and assessing the practical examinations were also developed at a regional workshop on qualification and certification of NDT personnel organized by the IAEA in 1987. There, however, remains the need to put it in a format such that it is suitable for circulation to and inviting comments from the international NDT community.

The IAEA has conducted three workshops on the methodology of production of standard test pieces. The main emphasis was on welding. There is a need to expand this exercise to other sectors of technology such as casting, forging, concrete and other ceramic materials. Also a guideline should be prepared as to what sort of standard test pieces are needed for specific sectors as outlined in ISO 9712. Then their designs and possible methods of fabrication should be given. The standard test pieces presently available from various manufacturers around the world along with their designs and tolerances on defects should next be reviewed. The IAEA and ISO can then consider persuading various training and certification agencies to use such recommended test pieces for their training and certification programmes.

(d) The uniformity in the standard of examinations and examination questions should be considered as the next important step towards achieving harmonization. Various certifying bodies in the developed countries maintain a bank of questions for conducting certification examinations. An example of this is the "questions bank of ASNT". Some other bodies, perhaps, also have similar published questions. The possibility of combining all of these and adding new ones such as to cover all the topics given in IAEA-TECDOC-628 for each method should be explored. The IAEA could then publish these as its own publication and recommend it for use to all the member states having certifying bodies.

A computer programme aimed at storage, retrieval and random selection of the questions could be a very helpful aid combined with the collection of questions.

The idea of keeping the questions restricted and confidential from the trainees and the applicants for certification is not very appealing. If someone can master answers to that many questions, he certainly deserves praise. In fact the emphasis should be on increasing the number of questions to, say, about 500 to 600 for each method. That will ensure that almost all the aspects of the subject have been covered. It will help the candidate tremendously if he had a clear idea of what sort of questions can be expected in the examination.

(e) NDT is being practised and developed in many countries and English is understood not in all of these. Therefore, for spreading the message for harmonization far and wide the essential ingredients such as text books, guidelines detailing practical work and the questions will need to be translated. As a first step the translations could be made for the United Nations-recognized languages and later on into other languages if the need be.

(f) The modern trends of teaching are increasingly utilizing the video camera and the video cassettes. For example, ASNT has already produced video cassettes for a number of NDT methods. Such efforts could also be made to produce video cassettes related to teaching the materials according to IAEA-TECDOC-628 and distributed to the NDT training agencies around the world.

(g) Rightly motivated and educated teachers and trainers in NDT can play an important role in bringing about uniformity in teaching and training ultimately bringing uniformity in NDT practices. IAEA realized this from the beginning by issuing the train-the-trainer guidelines. This concept needs to be further developed and incorporated and practised by the well known training and certifying bodies. If at least one premier training institute is selected in each country and its teachers motivated to adopt a certain methodology of teaching using same text books and identical test pieces, we would have advanced fairly well towards achieving harmonization.

(h) The question of specific sectors for certification need to be defined in narrower and clearer terms. Only then would harmonization be meaningful because persons trained and certified in well defined specific sectors in one country would mean to have same knowledge and competence as in other countries.

(i) While most of the regions have been encompassed by the IAEA regional projects for development and harmonization of NDT certification, there are others which still remain., e.g. the regions of Africa (other than North Africa), Eastern Europe and the states comprising former Soviet Union. For true international harmonization there is a need to plan projects focusing on these areas of the world as well.

(j) Finally there is a need to assess as to how far the requirements of ISO are being met by each country. A number of standards for assessment and accreditation of NDT laboratories and training institutions are already available to assess the capability of these organizations. A similar new accreditation standard needs to be formulated to check conformance to ISO 9712 which itself is trying to promote a new concept of harmonization at the world level in the filed of NDT. Then there should be a mechanism, perhaps established through IAEA, to monitor conformance to ISO 9712 with the help of new accreditation standard. Societies and institutions found to be satisfactory should be issued a conformance certificate just as, for example, the ISO 9000 conformance certificate. The NDT certificates issued by these ISO 9712-conforming societies and institutions should then be acceptable at the international level and their holders considered qualified and competent to work in the area of their certification in any country of the world.

9. SOURCES OF INFORMATION IN NDT

Industrial managers as well as the NDT managers and practitioners encounter a wide variety of test problems each of which may be unique in itself and may require special solution. This would, in principle require that each problem be tackled after a lot of thinking and experimental work for devising an appropriate NDT test technique and procedure. Fortunately quite a large proportion of these test situations and problems are quite identical and therefore, a lot can be learnt from the experience of others. This experience of others is usually available under what can be called the various sources of information in any field which is also true in the case of non-destructive testing. Management will really save a lot of effort and bother if it was knowledgeable & could retrieve, acquire and use the information available from these sources. It might be astonishing to discover that it has been able to find a tailor made almost exact solution to the test problem encountered instead of having to reinvent the wheel. This is specially true in the case of routine industrial inspection problems where a bulk of NDT technology is being applied anyway. Therefore, it is important to describe the numerous existing sources of information in the field of non-destructive testing and it is expected that all concerned will make best use of any one or all of these to find an expedient solution to their inspection problems and thus play a role for the rapid development of their departments & consequently the national economy.

9.1 BOOKS

Some categories of books include books on individual topics, books covering comprehensively a number of NDT techniques and those which are used as text books for various training courses. The number of books available is quite large and therefore it is difficult to include all of those here and consequently only some typical ones are mentioned. It is suggested that, if desired a complete list be compiled by consulting various information sources.

MC MASTER, R.C., Non-Destructive Testing Handbook, 1st Edition 1959 (Vol. I & II), American Society for Non-Destructive Testing, Columbus, Ohio.

Non-Destructive Testing Handbook (Vols 1–9), American Society for Non-Destructive Testing, Columbus, Ohio.

Volume 1–1982 Leak Testing, Mc MASTER, R.C.

Volume 2–1982 Liquid Penetrant Tests, Mc MASTER, R.C.

Volume 3–1985 Radiography & Radiation Testing, BRYANT, L.E., Mc INTIRE, P.

Volume 4–1986 Electromagnetic Testing, MESTER, M., Mc INTIRE, P.

Volume 5–1987 Acoustic Emission Testing, MILLER, R.K., Mc INTIRE, P.

Volume 6–1989 Magnetic Particle Testing, SCHMIDT, J.T., SKEIE, K., Mc INTIRE, P.

Volume 7–1991 Ultrasonic Testing, BIRKS, A.S., GREEN, R.E., Mc INTIRE, P.

Volume 8-1993 Visual and Optical Testing, ALLGAIER, M.W., NESS, S., MCINTIRE, P., MOORE, P.O.

Volume 9–1995 Special Non-Destructive Testing Methods, STANLEY, R.K., MOORE, P.O., Mc INTIRE, P.

SHARPE, R.S., "Research Techniques in Non-Destructive Testing (Volumes I to VIII), American Society for Non-Destructive Testing, Columbus, Ohio.

Volume I Non-Destructive Testing And Materials Evaluation Techniques.

Volume II Improving The Means of Collecting and Processing Test Data.

Volume III Signal Processing, Data Analysis and Information Presentation.

Volume IV Ultrasonic Attenuation and Scatter, Vibrational Analysis and Neutron Scatter.

Volume V Radiography, Ultrasonics, Infrared Technology, Electromagnetic Field Distribution and Non-Contact Inspection Using Lasers.

Volume VI Ultrasonics and Radiation Methods.

Volume VII Computer Processing of Digitized Radiographic Or Ultrasonic Test Data, Eddy Current Modeling, Design And Use of Microprocessors.

Volume VIII Computer and Microprocessor Control of Ultrasonic Testing, Quantitative Acoustic Emission Techniques, Eddy Current Technique, Vibration Technique and Automated Visual Inspection.

General Dynamics Classroom Training Handbooks (Five Volumes), American Society for Non-Destructive Testing, Columbus, Ohio.

CT-6-2 Liquid Penetrant Testing.
CT-6-3 Magnetic Particle Testing.
CT-6-4 Ultrasonic Testing.
CT-6-5 Eddy Current Testing.
CT-6-6 Radiographic Testing.

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HALMSHAW, R., Industrial Radiology, Allied Science Publishers Ltd, Also available from American Society for Non-Destructive Testing, Columbus, Ohio.

Choosing NDT, American Society for Non-Destructive Testing, Columbus, Ohio.
Non-destructive Inspection and Quality Control (American Society for Metals, American Society for Non-Destructive Testing, Columbus, Ohio.

SHARPE, R.S., Quality Technology Handbook, Butterworth, London (1984).

Metals Handbook, Vol. 17 on Non-Destructive Evaluation and Quality Control, American Society for Metals International, Metals Park, OH. (1989).

INTERNATIONAL ATOMIC ENERGY AGENCY, Ultrasonic Testing of Materials at Level-2, IAEA-TECDOC-462, Vienna (1988).

INTERNATIONAL ATOMIC ENERGY AGENCY, Industrial Radiography Manual for the Syllabi Contained in IAEA-TECDOC-628, Training Course Series No.3, IAEA, Vienna (1992).

9.2 NDT JOURNALS

The results of recent developments in the field of non-destructive testing applications as well as equipment, etc. are reported regularly in the NDT journals. The journals also act as a publicity media for various interests related to NDT and identify well in advance some of the important international events in the field. Some of the more popular journals are listed here:

Materials Evaluation, American Society for Non-Destructive Testing, Columbus, Ohio.

INSIGHT (previously the British Journal of NDT), British Institute of Non-Destructive Testing, North Hampton, UK.

Canadian Journal of NDT, NDE Institute of Canada, Hamilton, Ontario.

NDT International, Butterworth, Westbury House, Guildford, Surrey, UK

Ultrasonics, Butterworth, Westbury House, Guildford, Surrey, UK

NDT Australia, The Australian Institute for NDT, Box Hill, Victoria, Australia.

Non-Destructive Inspection, Japanese Society for Non-Destructive Inspection (JSNDI), Tokyo, Japan.

9.3 CONFERENCE PROCEEDINGS

The NDT community around the world is quite social and keeps getting together in the form of seminars, symposia, meetings and conferences. These get-togethers provide an avenue for an exchange of views and knowledge related to NDT mostly in quite a formal way by presentations of technical papers. These technical papers are then collected in a book form to constitute the proceedings. The proceedings can be topical i.e. related to a single topic or these can be more versatile covering a wide range of subjects. This would, of course, depend upon the nature of the get-together. Some typical proceedings compilations are listed here while information regarding many others may be obtained from sources in Sections 9.8 and 9.9.

Assuring Structural Integrity of Steel Reactor Pressure Vessels, International seminar, Berlin, August, 1979, Applied Science Publishers Ltd, London (1980).

Eddy Current Non-Destructive Testing, Workshop, Gaithersburg, Maryland, 3-4 November, 1977, Rep. PB81 166654 (NBS SP 589) (January, 1981).

Fundamentals of Acoustic Emission, Joint meeting of the acoustical societies of America and Japan, Honolulu, 27 November – 1 December 1978, University of California, Los Angeles (1979).

Industrial Applications of Infrared Technology, Symposium, London 7-8 November 1978, SIRA Institute Ltd, Chislehurst, Kent, UK(1978).

Industrial Radiography, Proceedings of 5th International Symposium, Mortsel, Belgium, March 1969, Afga Gevaert NV, Mortsel Belgium (1970).

Inspection and Quality Assurance, 4th National Conference, Birmingham, UK (1979).

Inspection of UK Reactors, Symposium Newport (United Kingdom), 30 September 1980, British Nuclear Energy Society (1981).

NDT Aspects of the Significance of Weld Defects, London, December 1971, The Welding Institute Abingdon, UK (1972).

NDT of Welds and Metal Joining, Proceedings of a 1968 symposium, Los Angles, California, March 1968, American Society for Non-destructive Testing (ASNT), Evanston, Illinois (1968).

New trends in NDT, Eurotest International Conference Brussels, Belgium, 24-26 March 1982, Durotest and Rurotest Media Sa (1982).

Non-destructive Testing, 5th international conference Montreal, May 1967, Queen's Printer, Ottawa (1969).

Non-destructive Testing, 7th international conference Warsaw, 4–8 June 1973, Polish Society of Mechanical Engineers.

Non-destructive Testing, 10th world conference, Moscow, 23–27 August 1982.

Non-Destructive Testing Standards, A Review, Symposium, Gaithersburg, Maryland, 19–21 May 1976 (BERGER, H, Ed.), American Society for Testing and Materials, ASTM STP 624 (1977).

Practical Applications of Neutron Radiography, Symposium, Gaithersburg, Maryland, 10–11 February 1975, (BERGER, H, Ed.), American Society for Testing and Materials, ASTM STP 586 (1976).

Quality Control and Non-Destructive Testing in Welding, International Conference London 19–21 November 1974, The Welding Institute, Abingdon, Cambridge (1974).

First World Conference on Neutron Radiography, San Diego, California, 7–10 December 1981, D. Reidel Publishing Co. Boston.

British Institute of Non-Destructive Testing symposium. Daresbury (UK). 23–26 Nov 1986, Br. J. Non-Destr. Test. (May 1988).

Annual British Conference On Non-Destructive Testing, Newcastle upon Tyne 16–18 Sep 1986, Engineering Materials Advisory Services Ltd (EMAS), 1987.

European Conference on Non-Destructive Testing London, 13–18 Sep. 1987, Pergamon Press, Oxford (1988).

World Conference on Non-Destructive Testing Amsterdam, 23–28 April 1989, Elsevier, Amsterdam (1989).

International Conference on Non-Destructive Evaluation in the Nuclear Industry, Tokyo, 25–28 Apr. 1988, American Society for Metals, Metals Park, OH.

Japan Conference on Radiation and Radioisotopes, Tokyo, 14–16 Nov. 1989, Nippon Aisotopu Hoshasen Sogo Kaigi Hobunshu (1990).

World Conference on Neutron Radiography, Osaka, 14–18 May 1989, Commission of the European Communities, Luxembourg.

Annual meeting of the Deutsche Gesellschaft für Zerstoerungsfreie Preufung e.V. (DGZfp): New tasks for Non-Destructive Testing. Trier, 21–23 May 1990. Deutsche Gesellschaft für Zerstoerungsfrei Preufung e.V. Berichtsband. V. 20

Conference of French Confederation for Non-Destructive Testing, Nice, 6–9 Nov. 1990, Soudage Tech. Connexes (Mar-Apr 1991)

American Society for Non-destructive Testing/American Welding Society (ASNT/AWS) Conference, New Orleans, June 1991.

International Symposium on Above Ground Storage Tanks, Houston, 14–16 Jan. 1992, Materials Technology Inst. of the Chemical Process Industry, Inc., St. Louis.

ASM Conference on Non-Destructive Examination (NDE) in the Nuclear and Pressure Vessel Industries, Albuquerque, 30 Apr. – 2 May 1992, Nuclear Engineering International (Jul 1992).

National Conference of the Australian Institute for Non-Destructive Testing, Melbourne (Australia), 19–21 Aug. 1991, Non-Destructive Testing — Australia, (Jan.–Feb. 1993).

Philippine Society for Non-Destructive Testing (PSNT) 7. Annual Convention, Manila, 13 Nov. 1992, Evaluator (Nov. 1991).

Annual British Conference on NDT, Cambridge Sep. 1992, British Journal of Non-Destructive testing (June 1993).

World Conference on Non-Destructive Testing. Sao Paulo, 8–23 Oct. 1992, Library of Comissao Nacional de Energia Nuclear, Brazil

National Seminar on the Assessment of IRPA Research Achievement in 5th Malaysian Plan: Industrial Sector, Kedah (Malaysia) 20–24 Dec. 1991.

European Conference on Advanced Materials and Processes (EUROMAT - 3), Paris, 8–10 Jun 1993, Journal de Physique 4 (Nov 1993).

Materials Testing Symposium: Progress in Testing and Quality Assurance, Bad Nauheim, Germany, 3–4 Dec 1992, TIB Hannover: RO 1685 (1992).

Nuclear Science and Technology Conference, Bangkok, 23–25 Apr. 1990, Office of Atomic Energy for Peace, Bangkok.

Quality and Safety in NDT, Coolangatta (Australia), 19–20 Mar. 1992, Non-Destructive Testing — Australia (July–Aug. 1993).

International Conference on Applications of Radioisotopes and Radiation in Industrial Development, Mumbai (India), 7–9 Feb. 1994, National Association for Applications of Radioisotopes and Radiation in Industry, India, Nov. 1994.

International Conference on Non-Destructive Evaluation in the Nuclear And Pressure Vessel Industries, Philadelphia, 10–13 Oct. 1993.

Republican Conference on Radioisotopes and their Applications, 24–26 Oct. 1995.

International Conference on Non-Destructive Evaluation in the Nuclear and Pressure Vessel Industries, Kyoto, 22–25 May 1995.

European Conference on Non-Destructive Testing, Nice, 24–28 Oct. 1994.

International Conference on the Application of Accelerators in Research and Industry — Topical Conference of the Division of Nuclear Physics (DNP) of the American Physical Society (APS), Denton, TX, 7–10 Nov. 1994, Nuclear Instruments and Methods in Physics Research, Section B, Beam Interactions with Materials and Atoms (May 1995)

Nuclear Science Symposium: Medical Imaging Conference. Norfolk, VA, 30 Oct. — 5 Nov. 1994, IEEE Transactions on Nuclear Science, Aug 1995.

Annual meeting of Deutsche Gesellschaft für Zerstoerungsfreie Pruefung e.V. (DGZfP): Non-destructive Materials Testing — 100 Years Of Roentgen Rays And Current Various Applications Of Non-Destructive Testing, Aachen (Germany), 22–24 May 1995, FIZ Karlsruhe.

9.4 STANDARDS

Standards have been developed to perform various non-destructive tests under uniform conditions for similar type of test specimens. Most standards aim at fixing test conditions or parameters such that following these conditions and procedures tests can be performed to produce test results which are uniform, reproducible and reliable. Besides, standards provide effective means of communication, promote economy in human effort and materials and promote production and trade by removal of barriers caused by differences in national practices. Different types of NDT standards exist. These include standards for terminology, standards for equipment, standards for testing, standards for education, training and certification and standards for acceptance and rejection. It is almost always possible to identify a standard to provide a solution to a particular problem from the large number of NDT standards that are internationally available. Given here are some of the well known standard issuing agencies of the world which could be approached for detailed lists of their standards. Also some of their standards related to NDT have been listed in Section 6.4.

International Organization for Standardization (ISO), 1 Rue De Varembe, Case Postale 56, Ch-1211, Geneva 20, Switzerland.

British Standards Institution (BSI), 389 Chiswick High Road, London W4 4AL, UK., Uninted Kingdom.

International Institute of Welding (IIW) (See Section 9.8).

Deutsches Institut für Normen (DIN), Burggrafenstrasse 6, D-10787 Berlin, Germany.

Standards Association of Australia (SAA), The Crescent, Homebush, NSW 2140, Australia.

Canadian Standards Association (CSA), 178 Rexdale Blvd, Rexdale M9W-1R3 Ontario, Canada.

Standards Council of Canada, 45 O'Conner Street, Suite 1200, Ottowa, Ontario KIP 6N7, Canada.

China State Bureau of Technical Supervision (ICSBTS), 4 Zhichun Road, Haidian District, P.O. Box 8010, Beijing 100088, China.

Japanese Industrial Standards Committee (JISC), Agency for Industrial Science and Technology, Ministry of International Trade and Industry, 3-1 Kasumigasekil, Chiyodaku, Tokyo, Japan.

American National Standards Institute, 11 West 42nd Street, 13th floor, New York, N.Y. 10036, United States of America.

American Society for Testing and Materials (ASTM), 1961 Race Street, Philadelphia PA 19103, United States of America.

American Society of Mechanical Engineers (ASME), United Engineering Centre, 345 East, 7th Street New York, NY 10017, United States of America.

9.5 PATENTS

Most industrial developments in processes as well as equipment are patented. The patent publications contain details of all the works for which patents have been issued. This information can be had from the patent organizations in different countries. The names of some of these organizations and the journals which they usually publish giving details of patents are given below:

British Patents Abstracts, Derwent Publications Ltd, London.

Official Journal (Patents), Patent Office, National Reference Library for Science and Invention (NRLSI), London.

Australian Official Journal of Patents, Trade Marks and Designs Commonwealth of Australia Patent Office, Canberra.

Canadian Patent Office Record, Canadian Patent Office, Ottawa.

German Patents Abstracts, Derwent Publications Ltd, London.

Official Gazette, United States Patent Office, US Government Printing Office, Washington, DC.

9.6 TECHNICAL REPORTS

A number of laboratories and institutes around the world are actively involved in carrying out research and development as well as exploring of new applications of non-destructive testing. The results of all these findings are compiled and reported in the form of internal technical reports before the summaries of results are published in the technical journals. These technical reports usually contain data and information in far greater detail than is available in the papers appearing in technical

journals. Some of these institutes around the world are listed below. Their public relations departments or libraries could be contacted for detailed lists of their reports as well as for possibilities and procedures for their acquisition. Details of these reports could also be had through various information services as listed in Section 9.12.

Australian Atomic Energy Commission Research Establishment, Lucas Heights, NSW, Australia (AAEC, ANSTO).

Defense Documentation Centre, Alexandria, Virginia, United States of America (AD-A).

Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Ontario, Canada (AECL).

UKAEA Atomic Energy Research Establishment, Harwell, Oxon, United Kingdom (AERE).

Aerojet Nuclear Company, Idaho Falls, Idaho, United States of America (ANCR).

Argonne National Laboratories, Illinois, United States of America (ANL).

Bundesanstalt für Materialprüfung, D-1000 Berlin 45, Germany (BAM).

Bhabha Atomic Research Centre, Trombay, Bombay, India (BARC).

Bettelle Columbus Laboratories, Ohio, United States of America (BMI).

Brookhaven National Laboratory, Upton, New York, United States of America (BNL).

Bettelle Pacific Northwest Laboratories, Richland, Washington, United States of America (BNWL).

USDOE Office of Scientific and Technical Information, Oak Ridge, Tennessee, United States of America (CAPE).

CEA Centre d'études Nucléaires de Saclay, 91-Gif-sur-Yvette, France (CEA).

Central Electricity Generating Board, London, United Kingdom (CEGB).

Council for Scientific and Industrial Research, Pretoria, South Africa (CSIR).

General Electric Company, Pleasanton, California, United States of America (GE and GEA, gesd gesp ETC).

Kernforschungszentrum Karlsruhe GmbH, Germany (KFK).

Siemens AG, Kraftwerksunion, Erlangen, Germany (KWU).

National Aeronautics and Space Administration, Greenbelt, Maryland, Goddard Space Flight Centre, United States of America (NASA, NSSDC).

National Technical Information Service, Springfield, Virginia, United States of America (NTIC)

9.7 PROFESSIONAL NDT SOCIETIES AND EXPERIENCED PERSONNEL

A good source of information related to NDT are the various professional bodies which exist in many countries. These have played a significant role in furthering the development of NDT. The societies organize meetings and conferences of NDT personnel and maintain a good record of their members. These are mostly responsible for publishing technical NDT journals, maintaining literature data banks and conducting training and certification of NDT personnel. Given below are some of the famous NDT societies in the world which could be contacted for any further information regarding the procedure for their membership or any other aspect of NDT.

Many of the developing countries of the Asia and Pacific region under the Regional Co-operation Agreement (RCA) have established the NDT societies. These include Pakistan, India, Bangladesh, Sri Lanka, Malaysia, Indonesia, Thailand, Philippines, South Korea and China. For addresses of these societies the personnel listed in Section 9.9 may be contacted. For other regions, relevant Sections of the IAEA may be contacted.

American Society for Non-destructive Testing (ANST), 1711 Arlingate Lane, P.O. Box 28518, Columbus, Ohio 43228-0518, United States of America, Tel : (614) 274-6003, Fax : (614) (274-6899), Telex : 245347.

Australian Institute of Non-Destructive Testing (AINDT), 191 Royal Parade, Parkville, Victoria 3052, Australia, Fax (03) 8904490, Telex : NATESM AA 31806.

Brazilian Association of Non-Destructive Testing (ABENDE); Rua Luiz Góes 2341; 04043-400 Sao Paulo SP, Brazil, Tel: 55-011-578-6677; Fax: 55-011-581-1164.

Belgian Association for Non-Destructive Testing (BANT); de Croylaan 2, B-3100 Leuven, Belgium, Tel: 32-16-29-08-43, Fax: 32-16-22-31-36

The Chinese Society for Non-Destructive Testing (ChSNDT), 100 Huihe Road, Shanghai 200437, China. Tel: 86-21-5440277, Fax: 86-21-5440277

Canadian Society for Non-Destructive Testing Inc. (CSNDT), Unit 47, 2400 Lukhnow Drive, Mississauga, Ontario L5S IT9, Canada. Tel: (416) 676-0785; Fax: (416) 673-9255

NDE Institute of Canada, 135 Fennel Avenue, West Hamilton, Ontario L8N 3T2, Canada. Tel: (905) 387-1655, Fax : (416) 5646080, Telex : 0618348

Japanese Society for Non-Destructive Inspection (JSNDI), 5-4-5 Asakusabashi, Taito-Ku, Tokyo-III, Japan, Fax : (03) 9636524

British Institute of Non-destructive Testing, 1 Spencer Parade, Northampton NNI 5AA, Tel: 44-1604-30124, Fax: 44-1604-231489, Telex : 31612OTSSG

Danish Society for Non-Destructive Testing, Park allé 345, DK-2605 Brondby, Denmark, Tel: 45-42-96-88-00, Fax: 45-42-96-26-36

French Confederation for Non-Destructive Testing (COFREND), 1 rue Gaston Boissier, F-75724 Paris Cedex 15, France, Tel: 33-1-4607-9405, Fax: 33-1-4607-9750

Associazione Italiana Prove Non Distructive (Italian Society for Non-destructive Testing),Via Foresti 5, I-25126 Brescia, Tel: (030)391716, Fax: (030) 392516

Nederlandse Vereniging Voor Niet Destructief Onderzoek (NVNDO), (Netherlands Association for Non-destructive Testing), Postbus 390, NL-3330 AJ Zwijndrecht, Tel: (078) 19-26-55

Norwegian Society for Non-destructive Testing, Secretariat: Norske Sivingeniores Forening, Kronprinsensgt, 17 Oslo 2, Tel: 02982501, Fax 02982333.

Deutsche Gesellschaft fur Zerstorungsfreie Prüfung eV (DGZFP) (German Society for NDT), Motardstrasse 54, D-13623 Berlin, Germany, Tel: 49-30-386-29910, Fax: 49-30-386-29917

Asociacion Espanola de Ensayos No Destructivos (AEND) (Spanish Society for Non-Destructive Testing) Avda Baviera 16 Bajo Izda; 28028 Madrid, Spain, Tel: 34-1-725-71-14, Fax: 34-1-725-71-14.

Schweizerishe Gesellschaft fur Zerstourungsfreie Prüfung (SGZP) (Swiss Association for Non-destructive Examination), Uberlandstrasse 129, CH-8600 Dubendorf, Switzerland, Tel: 41-1-823-55-11, Fax: 41-1-821-62-44, Telex : 53817
EUROTEST (International Scientific Association), Rue du commerce 20-22 Bte 7, B-1040 Brussels, Belgium, Telex : 22877

International Committee on Non-destructive Testing (ICNDT), c/o Dr. Baldev Raj, Indira Gandhi Centre for Atomic Research, Kalpakkam 603102, Tamil Nadu, India, Tel: 91-4117-40301, 40356, Fax: 91-4117, 40360, 40336, 40396

New Zealand Non-destructive Testing Association (NDTA), P.O. Box 12-241, Wellington, New Zealand, Tel: 64-3-5782272, Fax: 64-3-5782272

South African Institute for Non-Destructive Testing, P.O. Box 670, Bergvlei 2102, South Africa, Tel: 27-12-804-1620, Fax: 27-12-804-2009

International Institute of Welding, Abingdon Hall, Abingdon, Cambridge CBI 6AL, United Kingdom, Tel: (1223) 891162, Fax: (1223) 894180

Polish Society for Non-Destructive Testing, ul Rackawicka 20a, 41-506 Chorzow, Poland, Tel: (0-32) 463-501, 463-551, Fax: (0-32) 468-754

9.8 COMMUNICATIONS WITH RELATED PERSONS

Many a time the solution to a particular NDT test problem may be found by getting in touch with a person who is known to be knowledgeable in the field. A directory of NDT personnel in a particular country and even internationally is invariably maintained by the NDT societies listed in Section 9.8. For Asia and Pacific the appropriate persons to be contacted, beside the NDT societies, could be the national NDT Co-ordinators of Regional Co-operation Agreement (RCA) under the aegis of UNDP and IAEA. The network of national NDT co-ordinators is detailed below:

IAEA	C.R.Aleta, RCA Co-ordinator, Division of Technical Co-operation, International Atomic Energy Agency, Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, Austria.	Fax: [43] [1] 20607 Tel: [43] [1] 2060 x:22313
	A.A. Khan, Technical Office (NDT), Division of Physical & Chemical Sciences, International Atomic Energy Agency, Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, Austria.	Fax: [43] [1] 20607 Tel: [43] [1] 2060 26382

For other regions co-ordinators of other regional projects such as ARCAL, AFRA, West Asia, etc. of the IAEA may be contacted.

Australia	R. Gilmour, Materials Technology Department, Vic Roads, 60, Denmark Street, Kew Victoria, Australia 3101	Fax: [61] [3] 854 2048 Tel: [61] [3] 854 2147
Bangladesh	Md. Sanaullah, Atomic Energy Centre [AEC], P.O. Box No. 164, Ramna, Dhaka	Fax: [88] [2] 863 051 Tel: [88] [2]504355 509498 Tlx: 632203 BATOM BJ
China	Shi Ji-hua, NDT Centre for Nuclear Industry, Shanghai Nuclear Engineering Research and Development Inst., 29, Hong Cao Road, P.O. Box 233-008, Shanghai	Fax: [86] [21] 470 0681 Tel: [86] [21] 4364 700 Ext.4305

India	P.G. Kulkarni Atomic Fuels Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085	Fax: [91] [22] 556 0750 Tel: [91] [22] 551 9950
Indonesia	R. Setjo, Centre for the Application of Isotopes and Radiation, Pasar Jumat, P.O. Box 2/kby Lama, Jakarta Selatan 12240.	Fax: [62] [21] 769 1607 [62] [21] 756 0913 Tel: [62] [21] 756 0912
Japan	N. Ooka Oarai Establishment, JAERI, JAPAN.	Fax: [81] [292] 64 8480 Tel: [81] [292] 64 8364
Republic of Korea	Yong Moo Cheong, Non-destructive Testing Division, Korea Atomic Energy Research Institute, P.O. Box. 105, Yusong, Daejeon 305-606	Fax: [82] [42] 861 1184 Tel: [82] [42] 868 8091
Malaysia	Abd.Nasir bin Ibrahim, NDE Programme, Malaysian Institute Nuclear Technology Research, 43000 Kajang, Bangi, Selangor	Fax: [60] [03] 825 8265 Tel: [60] [03] 825 0501
Mongolia	D. Tserengiin, Nuclear Energy Commission, Government House Lear, 12, Ulaanbaatar	Fax: [976] [1] 310 011 Tel: [976] [1] 324 912 Tlx: 79309 GDVER MH
Myanmar	U. Aung Gyi, Physics and Engineering Department, Myanmar Scientific and Technological Research Department, No. 6, Kaba Aye, Pagoda Road, Yangon	Fax [95] [1] 65292 [95] [1] 65695 Tel. 65695, 63024, 64233
New Zealand	P. Hayward, Certification Board for Inspection Personnel, Hera House, P.O. Box 76-134, Manukau City.	Fax: [64][9] 2622856 Tel: [64][9] 2622885

Pakistan	Jamalluddin, National Centre for NDT, Scientific & Engineering Services, Pakistan Atomic Energy Commission, P.O. Box 1781, Islamabad	Fax: [92] [51] 44 6126 Tel: [92] [51] 413217 446127 Tlx: 5725 ATCOM PK
Philippines	A.J. Mateo, Inspection and Enforcement Unit, Nuclear Regulations, Licensing and Safeguards Division, Philippine Nuclear Research Institute, Commonwealth Avenue, P.O. Box 213, Diliman, Quezon City	Fax: [63] [2] 951 464 Tel: [63] [2] 967 343
Singapore	Sze Thiam Siong, Setsco Services Pte Ltd, 337 Telok Blangah Rd, Singapore 0409	Fax: [65] 270 0911 Tel: [65] 270 0988
Sri Lanka	T.M.R. Tennakoon, Atomic Energy Authority, 1/1 Ceramics Building, 696 Galle Road, Colombo 03	Fax: [94] [1] 501 467 Tel: [94] [1] 501 468
Thailand	V. Sripetdee Reactor Operation Division, Office of Atomic Energy for Peace, Vibhavadee Rangsit Road, Chatuchak, Bangkok 10900	Fax: [66] [2] 561 3013 Tel: [66] [2] 561 4079, 579 5230
Viet Nam	Nguyen Dang Nhuan, Ho Chi Minh Centre for Nuclear Techniques, 217 Nguyen Trai, QI, Ho Chi Minh City	Fax: [84] [83] 22 361 Tel: [84] [83] 93 775

9.9 AUDIO VISUAL AIDS

The NDT information has lately been transferred onto audio and visual tapes and, like in many other areas of technology, is a very effective way of disseminating NDT information specially for the purposes of education and training. Further information regarding this can be had from the NDT societies, for example ASNT, as listed in Section 9.8.

9.10 INFORMATION SYSTEMS AND DATABANKS

Quite a number of departments, organizations, institutions and societies maintain a good and up-to-date data banks of literature and information about NDT. Access to these sources of information can be usually had through memberships of the bodies operating these services. Similarly most of the organizations listed in Section 9.6 are known to have information data bases. Some well known organizations operating information systems and data banks in the field of non-destructive testing are mentioned here. No doubt there would be many others.

International Nuclear Information System (INIS),
International Atomic Energy Agency, P.O. Box 100,
A-1400 Vienna, Austria

Tel: 43 1 206022 883
Telex 1-12645
Fax: 43-1-20607
EARN/BITNET address
NIE@ IAEA1

Note: In each member state of INIS there is an INIS liaison officer who can be contacted for getting information through INIS.

INTERNET (International telecommunications and electronic messaging)

(i) The Internet Group,
Internet Business Centre (IBC),
395 S. Craig St., Pittsburgh, PA 15213,
United States of America

Tel: (412) 6889 696
Fax: (412) 6889 697
Email:
info@tig.com (Internet)

(ii) Internet Systems, Inc.,
T/A Library Systems and Services (LSSI),
200 Orchard Ridge Dr.,
Gaithersburg, MD 20878, United States of America

Tel: (301) 975-9800
Fax: (301) 975-9844

(iii) Delphi Internet Services Corporation,
1030 Massachusetts Ave.,
Cambridge, MA 02138

Tel: (617) 491-3393
800-695-4005
Fax: (617) 491-6642
Email: SERVICE
(Delphi Mail)

Note: Some of the INTERNET services include E-mail, Fax, remote login, file transfer protocol Archie, Gopher, Wais, Telnet and WWW, etc.

National Non-Destructive Testing Centre (NNTC),
Harwell Laboratory, 521 Didcot,
Oxfordshire OX11 ORA, United Kingdom

Tel: 235-433391
Fax: 235-432274

Federal Institute for Materials Research and Testing,
Non-destructive Testing Documentation,
Unter den Eichen 87, D-1000 Berlin, Germany

Tel: (30) 810 44628
Fax: (30) 811 2029

Texas Research Institute, Austin, Inc., Non-destructive Testing Information Analysis Centre, 415A Crystal Creek Dr., .Austin, TX 78746-4725 United States of America	Tel: (512) 263-2106 Fax: (512) 263-3530
American Society for Non-destructive Testing, Information Centre, 1711 Arlingate Ln., Columbus, OH 43228, United States of America	Tel: (614) 274-6003 Fax: (614) 274-6899
Idaho National Engineering Laboratory, Non-destructive Materials Characterization, Unit, P.O. Box 1625, Idaho Falls, ID 83415-2209	Tel: (208) 526-6124
Canterra Engineering, Ltd. Library, 6700 9 St. NE, Calgary, AB, Canada T2E 8K6	Tel: (403) 295-7676 Fax: (403) 295-7683
Canspec Group Inc. Branch Office Library, 2805 12th St. NE, Calgary, AB, Canada T2E 7G2	Tel: (403) 291-3126 Fax: (403) 250-1015
Louisiana State University, Division of Organized Research College of Basic Sciences, Baton Rouge, LA 70803, United States of America	Tel: (504) 388-8859 Fax: (504) 388-8826
Chen-Northen, Inc. Library, 370 Benjamin Lane, P.O. Box 7777, Boise, ID 83707, United States of America	Tel: (208) 377-2100 Fax: (208) 376-5349
Center for Advanced Cement-Based Materials, Northwestern Univ. 2145 Sheridan Rd., Evanston, IL 60208-4400, United States of America	Tel: (708) 491-3858 Fax: (708) 467-1078
Massachusetts Institute of Technology, Laboratory for Manufacturing and Productivity, 77 Massachusetts Ave., Rm.35-234, Cambridge, MA 02139	Tel: (617) 253-2113 Fax: (617) 258-8553
Acurex Corporation, 555 Clyde Avenue, P.O. Box 7555, Mountain View, CA 94039-7555, United States of America	Tel: (415) 964 3200 Telex: 322245
Welding Institute of Canada, 391 Burnhamthorpe Rd.E, Oakville, ON, Canada L6J 6C9	Tel: (416) 257-9881 Fax: (416) 257-9886
Singapore Institute of Standards and Industrial Research, 1 Science Park Drive,Singapore 0511, Singapore	Tel: 7787777 Fax: 7780086
National Institute of Standards and Technology, Materials Science and Engineering Laboratory, Neutron/Radiography Division, Neutron Radiography Facility, Gldg. 235, Gaithersburg, MD 20899, United States of America	Tel: (301) 975-6226

Battelle Northwest Laboratory, High Pressure/High Temperature Autos and Pipe Test Facility, P.O. Box 999, Richland, WA 99352, United States of America	Tel: (509) 376-3453
Advanced Manufacturing Centre, Cleveland State Univ., 1751 E., 23rd St. Cleveland, OH 44114, United States of America	Tel: (216) 687-4643 Fax: (216) 687-9260
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10. ORGANIZATION AND ADMINISTRATION OF NDT

10.1 BUYING AND SUPERVISING NDT SERVICES

As in every field of technology, the finest equipment, the brightest technicians and the most stringent regulations in non-destructive testing will be only marginally effective unless the resources are properly managed and administered.

The type of decisions that must be rendered by NDT engineers and technicians are often technically difficult, and must frequently be made under pressure of time or production. Valid second opinions are usually not easily available, if at all possible. It is for precisely this reason that most in-plant organizations have the inspection department one step removed from production, the Quality Assurance department reporting directly to the plant manager, or NDT responsibilities contracted out to a qualified third party who is relatively immune to internal plant politics.

The manager of NDT services in any organization will be loaded with many non-technical responsibilities, quite possibly in addition to being the final technical authority for NDT interpretation. He must select, train, and motivate competent staff. He must monitor the results, interpretations and reports being released by his people to clients, be they internal or external. He must ensure that equipment and supplies are available, adequate and properly controlled. He must ensure that his group's activities are supported with written procedures and practices, with current approvals by third parties, as appropriate. He is responsible for the safety of his own staff and the safe use of their equipment to avoid putting others at risk.

There are many valid reasons for using outside contractors for NDT services. The organization's own operation may have only occasional needs for any of the NDT methods; it may have a regular workload in one or more methods but only periodic requirements for radiography with its special equipment and safety considerations; it may wish to take advantage of the service company's breadth of work and the high level of collective and specialized experience it can thus bring to bear on the application. Perhaps it has a short- term staffing problem which leads it to go outside for NDT services while the recruiting or training of its own specialists is in progress.

In every one of these case, the process of selection, engagement and supervision are similar. Buying and supervising such specialist NDT services requires more care and safeguards than buying parts or cleaning services, for example.

The first check is the formal qualification of the individual(s) being assigned to the organization. There are several national and international systems for qualifying personnel. The most appropriate system should be selected before sending out an order, and compliance should be enforced. As with any specification, if the requirement is based upon a reasonable consideration of the need for the successful accomplishment of the task at hand and the resources available, acceptance of a lesser standard is a quality failure. Vendors will sometimes try to convince you of the equivalence of qualifications, or that the individual has "lots of experience" but has been too busy to write an examination, or that "you do not really need a level 2 for that inspection". The purchaser should insist that the specification is properly written and has to be met. If there are sound arguments for reducing the specification, it should be changed not ignored!

The second checkpoint is the equipment supplied by the contractor. Is it in good and safe working condition? Does it have the capacity to perform the inspection specified? Is it calibrated and the calibration records made available? Does the equipment meet the requirement of the code of construction, i.e., lifting power of an electromagnetic yoke, resolution capability of an ultrasonic transducer, etc.?

Once it has been established that the paper qualifications of the operator meet the specification, and the equipment is appropriate to the task, it is still necessary to confirm the capability of the operator through a job specific practical examination on a specimen provided by the buying organization, or through checking trade references who can attest to this competence on other similar tasks.

Many of these steps will become less necessary and formal as a trust relationship is developed with the supplier, however, one must always retain the right and capability of audit. The organization is paying for a highly specialized service and will be making major decisions based on the results.

There are a number of guidelines for the selection of NDT companies. Canada, for example, has a formal certification programme for welding inspection organizations (Canadian Standards Association Standard W178) which checks operator qualifications, equipment availability and calibration; and the availability of approved written inspection procedures. Any NDT service company which has an approved or registered quality programme conforming to the ISO 9000 series or a similar national standard would, in principle, have the basis for competence. Similarly any company which conforms to one of the national laboratory accreditation schemes would provide a good starting point. One NDT-specific document which provides excellent guidance for selecting and reviewing an NDT supplier is American Society for Testing and Materials (ASTM) E 543 - 88 Standard Practice for Determining the Qualification of Non-destructive Testing Agencies. ASTM E 543 says, in its scope.

> "1.1 This practice establishes minimum requirements for agencies performing non-destructive testing (NDT)."

While price (per hour, per task)should not be ignored, any review of quotations must go beyond the basic hourly rate. Since the cost of NDT is usually only a very small fraction of the cost if NDT is not done right, one can afford to pay a small premium for the quality and competence that one can be comfortable with. One should look closely at extras such as materials, travel time, overtime premiums and, of course, be prepared to take swift and decisive action if it is observed that the operator is either deliberately dragging out the job or is slow because he does not know what he is doing. If one asks for estimates of execution time with quotations, it is possible to have a rough check on the expected duration.

In summary, when buying and supervising NDT services, one should follow the same principles which would apply to the buying of any technical service i.e. careful qualified supplier selection, verification of conformance , and surveillance. If the task warrants, and the organization does not have the technical capability on staff to supervise, it is advisable to engage an independent auditor.

10.2 THE SPECIAL ROLE OF THE LEVEL 3 IN MANAGEMENT

Most national and international standards for the qualification of non-destructive testing personnel, including ISO 9712, classify NDT operators from levels 1 through 3, with level 3 being the highest. According to ISO 9712 :

> "An individual certified to NDT level 3 shall be capable of assuming full responsibility for a test facility and staff, establishing techniques and procedures, interpreting codes, standards, specifications and procedures, and designating the particular test methods, techniques and procedures to be used. He shall have the competence to interpret and evaluate results in terms of existing codes, standards and specifications, a sufficient practical background in applicable materials fabrication and product technology to establishing acceptance criteria, assist in establishing acceptance criteria where none are otherwise available, general familiarity with other NDT methods, and the ability to train level 1 and level 2 personnel."

The capabilities attested to by a level 3 certificate are by no means the only criteria for a management or supervisory job. The definition does, however, establish minimum technical competence usually gained through years of practical experience. While the training and experience requirements for eligibility under the standard are somewhat reduced for individuals with advance education (such as an engineering or science degree), one cannot become certified without a practical examination.

Given that the level 3 person has this extra level of competence how then does one best fit him into the organization? Ideally, the QA manager, chief inspector, or NDT manager will be the level 3 person, but where company policy or politics rule this out, it is common to put the level 3 in a senior staff position where he can be a

technical adviser and trainer and writer of procedures. For NDT service companies , it is essential that a certified level 3 individual be in a position of responsibility and that this level of support be available to the customer. The company should further have a level 3 qualification for every method it offers.

Reliability and competence in NDT requires training, directed experience and qualification examinations. This process is good for the individual and his employer because there is constant challenge and measured progress as he works his way up through the levels of certification in each method. On the other hand, it is expensive even if the training is done by the employer using his own resources. An outside agency must recover this cost from its clients. In any case the cost of competence, quality and hence reliability is many times smaller than the potential cost of improperly done inspection.

10.3 TYPICAL LABORATORY/SERVICE FACILITY ORGANIZATION

As the level 3 person's position in the organization depends highly on the company structure itself, so does the manner in which the NDT facility is appended to the company structure. Among the factors which must be considered are the following:

a. **Independence from undue influence**: The NDT group must be able to make its inspection decisions without being subjected to pressure from line production or maintenance supervision to ignore or change unpleasant test results.

b. **Access to necessary resources**: The group must have the equipment and supplies needed to carry out its functions in a timely and safe manner. Adequate provision must be made for standards and reference library and there must be a budget for training.

c. **Clerical staff:** The department will produce reports which become important documents, a basis for action or a record for traceability. Procedures manuals, often prepared at great expense must be maintained and available for controlled access.

d. **Internal quality control:** The department should have someone, necessarily senior but not necessarily full-time, who monitors and audits the NDT operations to eliminate bad practices and to ensure that procedures manual is followed.

e. **Hierarchical team structure:** The structure should ensure that more junior people are working under direct supervision of more experienced staff, for their formal development, for work control, and to meet the requirements of the certification standard.

f. **Work flow control:** Project or job number must be assigned to each batch or task. Records must be kept of the number of parts received, when were they inspected and the results of such inspections. It should be clear who signs the final inspection report and who can release the parts to the client.

g. **Crew rotation and job assignment system:** Individuals must be assigned to tasks in line with their competence and their development plan. New employees should be rotated between supervisors to broaden their work exposure.

h. **Equipment maintenance and calibration:** Provision must be made for cleaning and checking the equipment after each use, storing it safely and securely, calibrating and maintaining calibration records, and for repairs and replacements when necessary.

Two typical organizational structures for different types of NDT laboratory facilities are shown in Figures 10.1 to 10.3.

10.3.1 Typical laboratory and equipment layouts

It is impossible to prescribe a standard layout for an NDT laboratory. The actual size and shape will always be determined by such external factors as available space, location, size and volume of work to be processed and financial resources. There are certain technical constraints which are mainly due to such things as inspection flow logic (in magnetic particle inspection, liquid penetrant inspection), to safety and processing parameters (for radiographic exposure facilities and film handling) and to power and cleanliness requirements (for ultrasonic and eddy current testing).

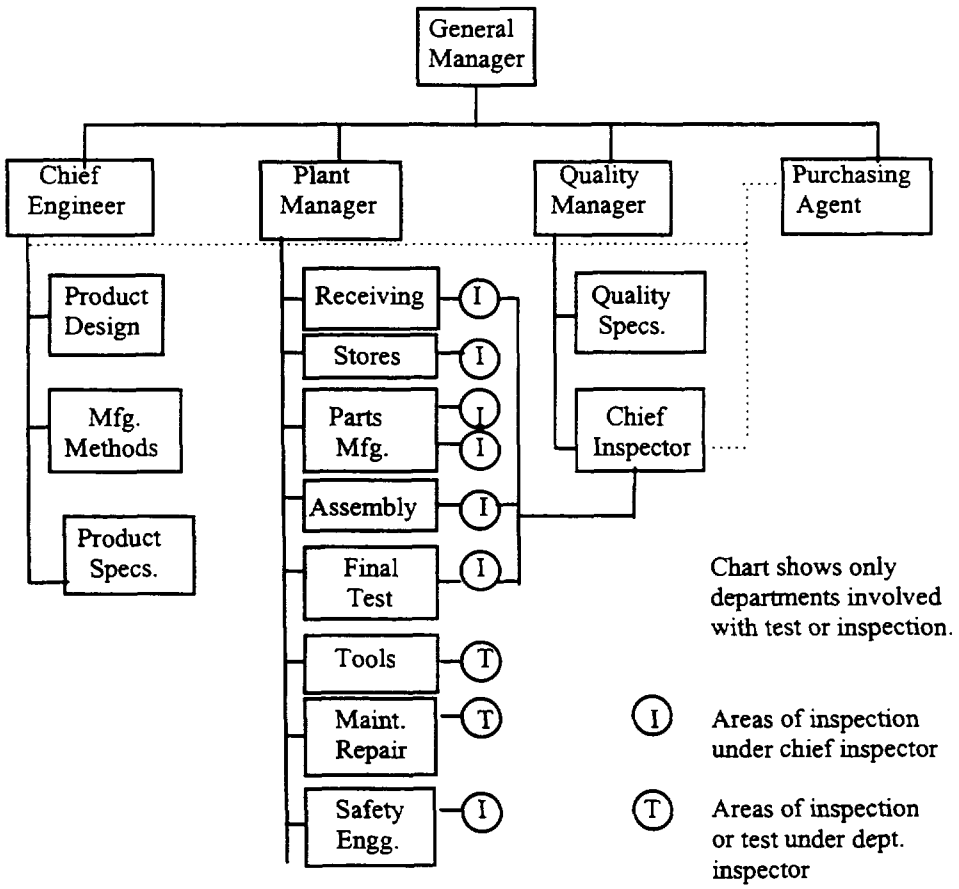


Figure 10.1 : A large manufacturing operation.

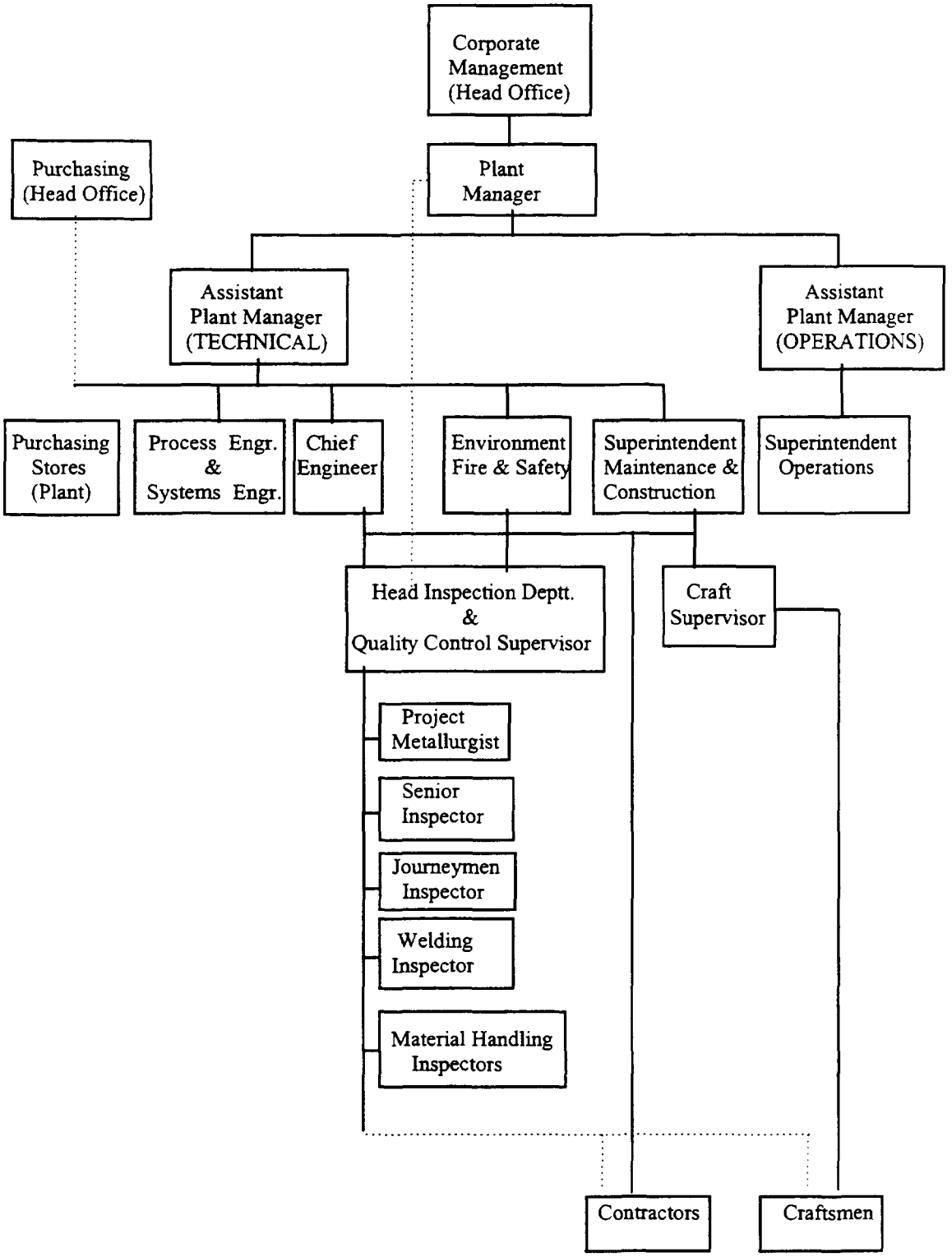
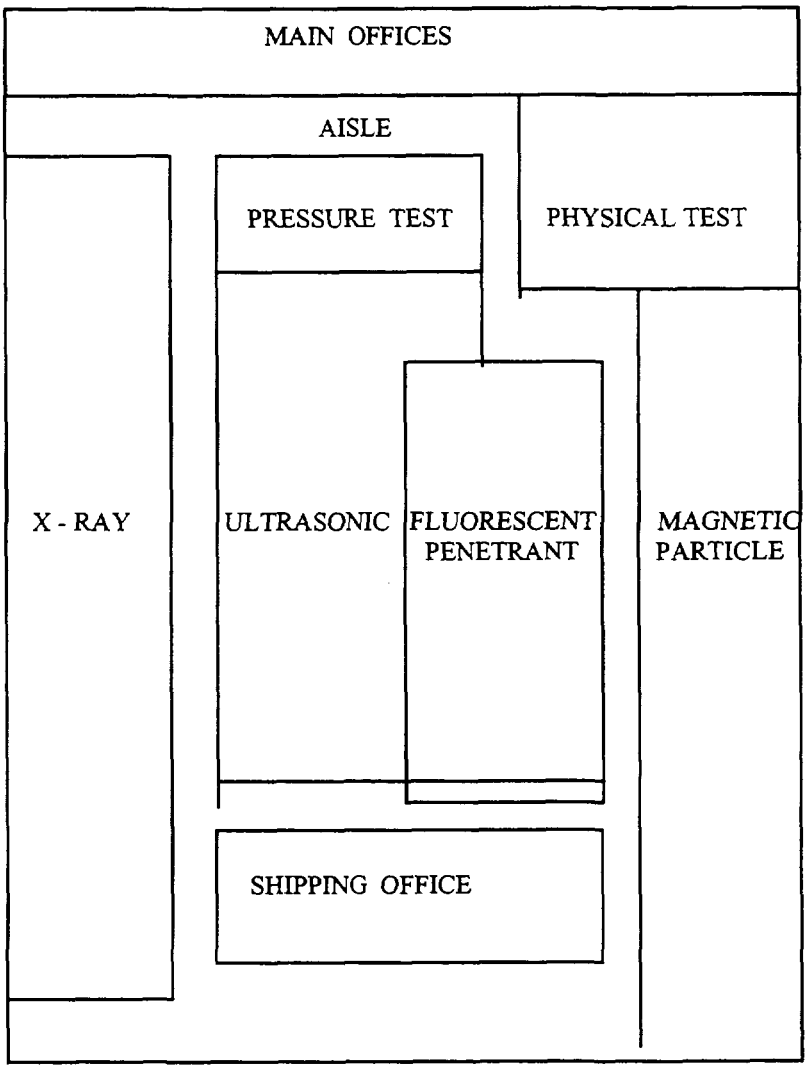
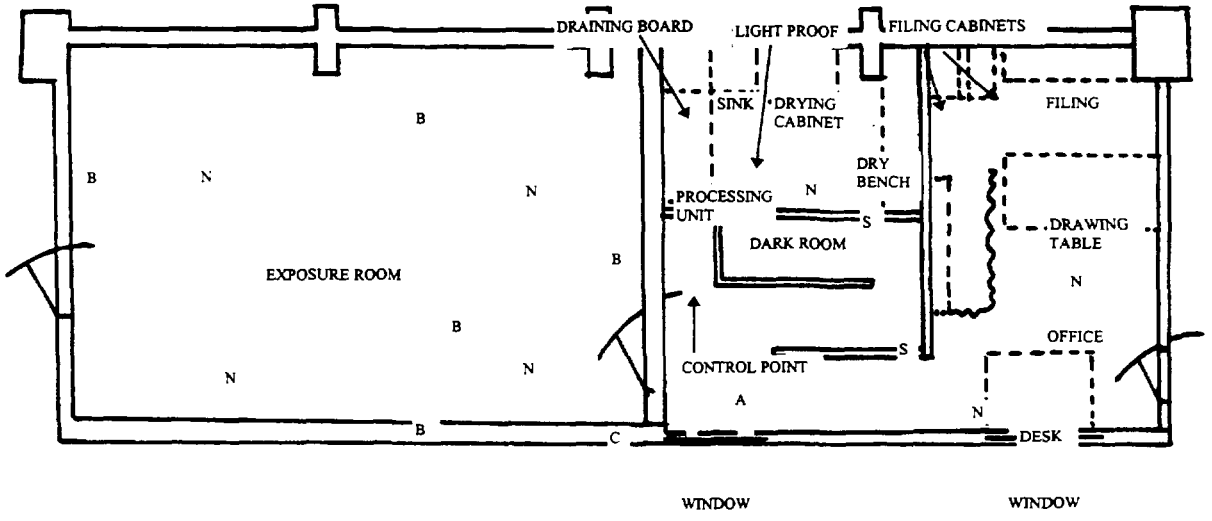


Figure 10.2 : An operating plant.

(a)





(b)

Figure 10.3 : (a) Typical NDT laboratory floor plan.
(b) Floor plan for radiographic section.

10.3.2 Equipment selection

The range of equipment needed for an NDT laboratory will depend on the applications and the frequency and conditions of use. Usually, external standards will determine the necessary performance capabilities. While the basic price is a major consideration, one should not lose sight of other factors which, in the long term, may have more influence both in terms of capability and economics. Some of these other considerations are as follows:

a. **Capacity:** The cost of a 160 kV X ray machine may be only 60% of that for a 200 kV unit, however if you have occasional need for the higher penetrating power of the 200, you are much better off to buy the higher powered unit.

b. **Portability:** Most NDT laboratories involve a need for inspection to be carried out remote from the laboratory, even if only a few hundred metres away in the welding shop. Modern portable equipment generally does not sacrifice capacity and durability for smaller size.

c. **Power requirements:** Some equipment, notably fixed magnetic particle units require greater than mains voltage.

d. **Storage and licensing requirements:** Radioactive isotopes have special requirements above and beyond those for X ray machines; compliance is expensive.

e. **Ruggedness and maintainability:** Equipment should be selected for its ability to stand up to the use you intend to make of it. You should be able to make at least basic repairs without sending it back to the manufacturer.

f. **Supplier support:** The speed and level of service available to you from your local supplier is also something that should be verified before buying.

10.4 FIELD OPERATIONS AND PORTABLE EQUIPMENT

A generic table of equipment for a mobile unit capable of providing inspection services in four NDT methods is detailed below. Obviously this list is subject to specific local requirements, type of work and volume.

Light truck with mobile darkroom & portable generator.

Radiographic equipment:

- Ir-192 camera, source (50–100 Curie) and related safety equipment for storage, handling & emergency.

- Film handling, developing and storage facilities including chemicals and tanks, hangers, cassettes, safelights, lead figures, attachment devices, number tapes, etc.

Ultrasonic equipment:
- Portable flaw detector, batteries and power pack.
- Selection of transducers for thickness measurement and weld inspection, range of sizes, angles and frequencies.
- Calibration blocks, spare cables, couplant, etc.

Magnetic particle equipment:
- Portable electromagnetic yoke & flexible legs.
- Ultraviolet lamp & spare bulbs.
- Assortment of wet fluorescent and dry powder magnetic particles, aerosols or spray applicators.

Liquid penetrant equipment:
- Selection of aerosol based visible and fluorescent dyes, developers, and solvent cleaners.

- Cleaning materials, including cloths and brushes.

General inspection and support tools:
- Measuring tape, steel rules, magnifying glass, weld gauges, camera, screwdrivers, pliers, haywire and electrical tape.

The approximate cost of this fully equipped unit would be about $60 000 to $75 000 including the vehicle.

10.5 SAFETY

One of the primary concerns of the NDT laboratory manager has to be safety. While the NDT community immediately links safety with radiation safety, there are other issues:

a. **General industrial safety:** It is the responsibility of the NDT manager to ensure that his personnel are aware of the safety precautions that must be taken when working in industrial plants. Because safety orientation is usually a requirement enforced at the time of employment, the plant personnel may take if for granted that the NDT contractor personnel have been similarly oriented. General industrial safety training should be provided before field assignments which should cover such topics as electrical hazard, toxic chemicals, working at heights, locking out of rotating equipment, working in enclosed spaces and flammability.

b. **Controlled chemicals:** While the chemicals used in NDT (film-processing, penetrant systems, magnetic ink, ultrasonic couplant, etc.) have generally been selected to be non-toxic and non- irritating, the operator must be aware of general precautions and legal restrictions on their storage, handling and disposal.

c. **Radiation safety:** The NDT manager and his designated radiation safety officer must be continually aware of their legal and moral obligations to prevent unnecessary exposure of controlled staff and inadvertent exposure of

uncontrolled personnel. In many countries a safety infraction can result in the loss of an operating licence, and often in more serious penalties. On site the NDT personnel should have contact numbers of radiation safety organizations. They should also be aware of the steps that need to be taken in case of emergency such as a vehicle accident or the source getting stuck in the guide tube of the camera.

10.6 ETHICS

The scope and importance of the decisions that must be reached by the NDT manager and his staff, and those to whom they report, make it critical that the activities of the department be conducted with the greatest integrity. For example, if a technician is working on an elevated chemical line at the end of a shift, has two more thickness readings to take, and the battery on his ultrasonic meter dies, will he have the integrity to come down from his perch, change the battery and go back to take the reading or perhaps consult someone who can decide on the importance of those two readings or will he take the easy route of making up the numbers based on previous readings?

Will the level 2 film interpreter reviewing several hundred radiographs at the end of the shift decide that one joint has been missed, or that one of the radiographs is not clear enough to read, and send his crew out to reshoot or will he substitute another similar radiograph?

Will a UT operator who has located a possible flaw in a rotating shaft stand by his interpretation, despite pressure from the maintenance superintendent who wants to keep the equipment on line?

There are several codes of ethics published for NDT personnel, perhaps most notably that by the American Society for Non-destructive Testing. The manager of the NDT group must adhere to the highest level of ethics and insist on conformance by his staff. Failure to do so can result in loss of life, loss of product, plant downtime, and loss of credibility for the entire NDT community.

10.7 LEVELS OF RESPONSIBILITY IN AN NDT ORGANIZATION

10.7.1 Responsibility for safety

The NDT manager is responsible for the safety of his staff and of the public. This means that he must be aware of and implement:

- Government regulations with regard to hygiene, building, scaffolding, use of *radioactive equipment, use of electric equipment, etc.*
- Proper care and handling of hazardous materials (toxic and inflammable).
- Provision and use of safety equipment.

10.7.2 Responsibility for planning

He must identify his short term and long term aims and objectives, e.g. is he going to specialize in only one type of NDT or cover all methods, specialize in only one industry or try to be general. What does he want his organization to be doing in 1 years time, 5 years' time, 10 years' time, etc. What is the market place doing i.e. trends which can give him business opportunities. What staff does he have? What are their strengths and weaknesses? Is training required or will he steal staff from other organisations when required?

10.7.3 Responsibility for organization

He is responsible for effective management systems leading to locating work, costing and submitting bids, programming work (staff, equipment), ensuring successful completion, correct reporting, correct invoicing, ensuring payment of all accounts, chasing bad debts, buying new equipment, carrying out research and development to produce new test procedures, hiring and firing of staff, maintaining equipment, conducting quality audits, exercising technical control, etc.

10.7.4 Responsibility for quality assurance manual

He is responsible for the development of the quality assurance manual for his organisation. This manual should:

- Detail all the policies, procedures and practices of the organisation and give cross references to other organisation documents.
- Be a working document for all his staff.
- Contain instructions for its own review and updating as practices or policies change.
- Be the basis for self audit of the organisation by management.
- Describe procedures for training staff and monitoring their performance.
- Describe procedures for monitoring the validity of results produced by new staff or by new techniques.
- Detail the recording and reporting system so that there is a traceable link between the test and the report to allow repeatability.
- Indicate which calibration records must be kept and by whom. For example, records of:
  - -UT equipment
  - -UT probes
  - -Intensity of black light
  - -Colour intensity of penetrants
  - -Efficiency of used emulsifiers
- System checks with reference test pieces
- State who is responsible for checking / viewing of radiographs and how many radiographs have to be checked and where the result of the check is to be recorded., e.g.
  - -Repetitive work — 2% checked
  - -General jobbing work — 20% checked
- State who is responsible for visits to site to check ultrasonic work and where the records of the visits have to be recorded.

- State who is responsible for checks on developer strength and temperature.
- State who is responsible for routine checks of the field strength in magnetic particle testing using portable flux indicators or magnetic field meters.

10.7.5 Responsibility for test method manual and for ensuring that test methods are followed

The test method manual should contain copies of all standard test procedures. In addition all staff performing a test must have a copy of the relevant code, standard or test procedure and procedures must be followed exactly. Any modifications to standard procedures are only acceptable if the effects of the modifications have been documented and can be justified technically. Any variations must be noted and acknowledged in test documents. Procedures must also be in place to update codes and standards.

Any internal test procedures or such procedures which are not covered by codes, must be documented and verified.

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