# 3D Modelling of Thermofluid Flow in Friction Stir Welding

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# 3D Modelling of Thermofluid Flow in Friction Stir Welding

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## Abstract

Friction stir welding is a complex process including interactions between thermal, metallurgical and mechanical phenomena. The heating is provided by the mechanical dissipation due to the strains and the contact conditions between the tool and the material.

This paper describes a numerical model to simulate the temperature profile during the steady-state of the process. This fully coupled model is based on the Finite Element Method considering an incompressible non-Newtonian fluid. The stress equilibrium, the energy conservation and the mass conservation are studied in an Eulerian frame. The objectives of such a 3D model are, on one hand, the understanding of physics and, on the other hand, the development of a predictive tool allowing to reduce the number of experiments needed to design new tools. An example is presented for an aluminium alloy 7075.

**Keywords:** Friction Stir Welding, Finite Element Method, thermofluid analysis.

**Introduction**
Friction stir welding is an emerging welding process which was developed initially for aluminium alloys by the TWI [1]. This process involves strong interactions between thermal, metallurgical and mechanical phenomena as shown in Fig. 1.

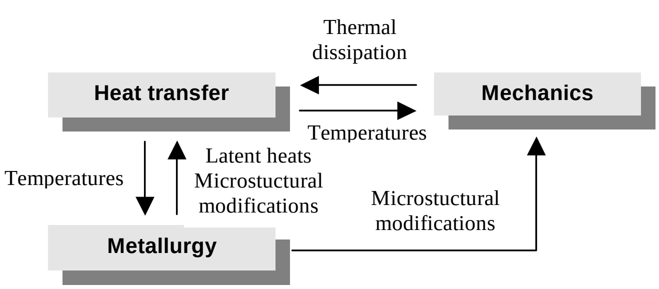


*Figure 1: Coupling between heat transfer, metallurgy and mechanics.*

FSW is details in [1]. For this process, the numerical modelling seems to be extremely valuable for the understanding of the residual stresses, the distortions and the microstructure modifications. To model these effects, the heating needs to be carefully simulated.
Many efforts have been spend both analytically and numerically [2]. The objectives of the simulation are, on one hand, the understanding of physics and, on the other hand, the development of a predictive tool allowing to reduce the number of experiments needed to design new tools [3,4].

In this paper, a three-dimensional model is presented accounting for the thermal and the mechanical phenomena in a fully coupled approach. This model is based on the Finite Element Method. The thermal interaction between the tool and the material is neglected. The stress equilibrium problem, the heat transfer problem and the mass conservation are solved for the stationary step of the process. The material is assumed to be as a viscous non-Newtonian fluid [1,2]. Therefore the problem can be studied in an Eulerian frame where the mechanical stress are calculated from the velocity field and the thermal dissipation can be easily deduced.

The first part of the article will detail the thermo-mechanical problem and the boundary conditions using an Eulerian approach. The second part deals with the finite element modelling. Finally, an example is presented.

## Physical coupling

In the Friction Stir Welding simulation, we are interested in the combined convective and conductive transport of thermal energy in the workpiece material due to the local mechanical dissipation. The equilibrium of a continuous medium $\Omega$ with boundary $\partial\Omega$ is governed by three global conservation principles which are the stress equilibrium, the energy conservation and the mass conservation.

**Stress equilibrium**

The stress equilibrium equation must be obtained for each material element. Including dynamic and static effects internally, and gravity as an external body force, the equation of motion in an homogenous medium Ω can be written as follows:

$$\overrightarrow{div}\left(\overline{\overline{\sigma}}\right)+\rho.\vec{g}=\rho.\frac{D\vec{v}}{Dt} \qquad (1)$$

where $\overline{\overline{\sigma}}$ is the Cauchy stress tensor, $\rho$ is the density, $\vec{g}$ is the acceleration vector due to the gravity, $\vec{v}$ is the velocity vector and $\frac{D}{Dt}$ is the material derivative operator $\frac{D}{Dt}=\frac{\partial}{\partial t}+\vec{v}.\overrightarrow{grad}(\ )$.

In this study, the inertial and gravity forces are neglected (much smaller than the static effects):

$$\overrightarrow{div}\left(\overline{\overline{\sigma}}\right)=\vec{0} \qquad (2)$$

At typically FSW temperatures, it is reasonable to assume that the stresses are perfectly viscous for aluminium alloys [1]. Thus, the total stress tensor $\overline{\overline{\sigma}}$ can be decomposed into one hydrostatic part and one viscous part as for a viscous incompressible fluid:

$$\overline{\overline{\sigma}}=\overline{\overline{S}}-p.\overline{\overline{I}} \qquad (3)$$

where $p$ is the hydrostatic pressure, $\overline{\overline{I}}$ is the unit tensor and $\overline{\overline{S}}$ is the viscous stress tensor.

The stress equilibrium equation can therefore be written as:

$$\overrightarrow{div}(\overline{\overline{S}})-\overrightarrow{grad}(p)=\vec{0} \qquad (4)$$

The viscous stress tensor $\overline{\overline{S}}$ is related to the strain-rate tensor $\overline{\overline{D}}$ using a Norton-Hoff behaviour law:

$$\overline{\overline{S}}=2.\mu.\overline{\overline{D}} \qquad (5)$$

where $\overline{\overline{D}}$ is the strain-rate tensor defined from the velocity field

$$\overline{\overline{D}}=\frac{1}{2}.\left(\overline{\overline{grad}}\left(\vec{v}\right)+\overline{\overline{grad}}^{T}\left(\vec{v}\right)\right) \qquad (6)$$

$\mu$ is an effective viscosity defined as follows [5]:

$$\mu=K.\left(\sqrt{3}.D\right)^{m-1} \qquad (7)$$

$K$ and $m$ are the consistency and the sensibility of the material, and $D$ is the equivalent strain rate:

$$D=\sqrt{\frac{2}{3}\overline{\overline{D}}:\overline{\overline{D}}} \qquad (8)$$

The boundary conditions on the boundary ∂Ω of a medium Ω can be written as:

- Dirichlet boundary conditions on surface $\partial\Omega_v$:

$$\vec{v}=\vec{v}_d$$

- Neumann boundary conditions on surface $\partial\Omega_T$:

$$\overline{\overline{\sigma}}.\vec{n}=\vec{T}$$

with $\partial\Omega=\partial\Omega_v\cup\partial\Omega_T$ and $\partial\Omega_v\cap\partial\Omega_T=\varnothing$

The friction between the tool and the workpiece is of Neumann boundary conditions. The contact is modelled by the Norton law [6]. In this model, the friction stress depends on the differential velocity $\Delta\vec{v}$ between the tool and the workpiece:

$$\vec{\tau}=\beta.K.\left|\Delta\vec{v}\right|^{\psi-1}.\Delta\vec{v} \qquad (9)$$

where $\vec{\tau}$ is the shear stress, $\beta$ and $\psi$ are the contact parameters.

**Conservation of energy**

For an incompressible material, the law of conservation of energy (or First Law of Thermodynamics) can be expressed as:

$$\phi-div\left(\vec{q}\right)=\rho.C.\frac{D\theta}{Dt} \qquad (10)$$

where $\theta$ denotes the temperature, $\vec{q}$ the heat flux density vector, $\phi$ is the viscous dissipation [7] and $C$ is the specific heat.

In a stationary Eulerian frame, this expression becomes:

$$\phi-div\left(\vec{q}\right)=\rho.C.\vec{v}.\overrightarrow{grad}\left(\theta\right) \qquad (11)$$

The non linear isotropic Fourier constitutive relation is used to model the heat flux density:

$$\vec{q}=-\lambda(\theta).\overrightarrow{grad}\left(\theta\right) \qquad (12)$$

where $\lambda(\theta)$ is the thermal conductivity.

The boundary conditions on the boundary ∂Ω of a medium Ω can be written as:

- Dirichlet boundary conditions on surface $\partial\Omega_\theta$ :

$$\theta=\theta_d$$

- Neumann boundary conditions on surface $\partial\Omega_q$ :

$$\vec{q}.\vec{n}=q$$

with $\partial\Omega=\partial\Omega_\theta\cup\partial\Omega_q$ and $\partial\Omega_\theta\cup\partial\Omega_q=\varnothing$

$q$ is a prescribed heat flux which is temperature dependent:

$$q=H_{ext}.(\theta_{ext}-\theta) \tag{13}$$

where $H_{ext}$ is a convective heat transfer coefficient and $\theta_{ext}$ is the outside temperature.

The thermal contact conditions at the tool shoulder includes the friction heat dissipation and the heat exchanged between the tool and the workpiece [8]:

$$q=\frac{E_{material}}{E_{tool}+E_{material}}.\beta.K.\left|\Delta\vec{v}\right|^{\psi+1} + H_{shoulder}.(\theta_{tool}-\theta_{material}) \tag{14}$$

where $H_{shoulder}$ is a heat transfer coefficient, $\theta_{tool}$ and $\theta_{material}$ are the interface temperatures of the tool and the workpiece, $\frac{E_{material}}{E_{tool}+E_{material}}$ is the fraction of the dissipated heat received by the plates calculated by means of the effusivity coefficients $E$ :

$$E=\sqrt{\lambda.\rho.C} \tag{15}$$

The thermal interaction between the tool and the workpiece is assumed to be much smaller than the dissipated heat. Therefore, the tool does not need to be modelled:

$$q\approx\frac{E_{material}}{E_{tool}+E_{material}}.\beta.K.\left|\Delta\vec{v}\right|^{\psi+1} \tag{16}$$

**Conservation of mass**

The continuity equation states that mass cannot be lost or gained. It implies that velocity fields must be of the form:

$$\frac{\partial\rho}{\partial t}+div(\rho.\vec{v})=0 \tag{17}$$

Introducing the thermal dependency of the density for steady-state conditions in an Eulerian frame, the continuity equation becomes:

$$div(\vec{v})-\alpha(\theta).\overrightarrow{grad}(\theta).\vec{v}=0 \tag{18}$$

where $\alpha$ is the thermal expansion coefficient:

$$\alpha(\theta)=-\frac{1}{\rho(\theta)}.\frac{\partial\rho}{\partial\theta} \tag{19}$$

This equation can be considered as the incompressibility condition.

## Finite element modelling

This section presents the finite element procedure developed to obtain an approximated solution of the formulation presented previously. The stress equilibrium equation and the mass conservation equation are also called the Stokes equations. To approximate the solution of these equations, the velocity spatial discretization and the pressure spatial discretization must be properly choosen to satisfy the inf-sup condition of the mixed method theory [9]. Moreover, it is well known in the finite element literature that for large mesh-Peclet number (dominated advection), spurious oscillations are frequently detected in the numerical approximation of Eq.11 which need to be damped through the use of the SUPG method [10,11].

To satisfy the inf-sup condition of the mixed method theory, one possibility is the use of a tetrahedral finite element. The velocity field is discretized with continuous piecewise linear functions $N_1$, $N_2$, $N_3$ and $N_4$ associated to nodes 1, 2, 3 and 4 enriched by a bubble function $N_b$ associated to a fifth node $b$ corresponding to the centroid of the finite element [12] (Fig. 2).

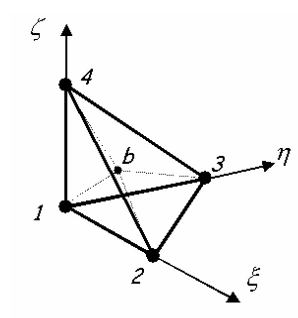


*Figure 2: Tetrahedral finite element.*

The velocity is expressed in the following way in the finite element:

$$\vec{v}(\xi,\eta,\zeta)=\sum_{i=1}^{4}N_i(\xi,\eta,\zeta).\vec{v}_i+N_b(\xi,\eta,\zeta).\vec{v}_b \tag{20}$$

where $\vec{v}_i$ is the velocity at each node $(i=1,2,3,4)$ and $\vec{v}_b$ is the velocity at node $b$ .

The pressure and the temperature are approximated as follows:

$$p(\xi,\eta,\zeta)=\sum_{i=1}^{4} N_i(\xi,\eta,\zeta).p_i \qquad (21)$$

$$\theta(\xi,\eta,\zeta)=\sum_{i=1}^{4} N_i(\xi,\eta,\zeta).\theta_i \qquad (22)$$

where $\theta_i$ and $p_i$ are the temperature and the pressure at each node $(i=1,2,3,4)$.

The Finite Element Method is based on the variational formulation of the problem obtained by the weighted residual method and the Green-Gauss theorem (integration by parts). When the Finite Element Method is applied to equations (4), (11) and (18) in a Galerkin approach, it leads to a non-linear equation system. An approximated solution is obtained with a Newton-Raphson iterative procedure but a mathematical regularization must be introduced in the Norton-Hoff law for numerical reasons [6].
This model has been developed in the software SYSWELD® which is dedicated to the simulation of welding and heat treatment.

## Application

In this section, an example is presented. The temperature are calculated during the welding of two plates made of aluminium alloy 7075. The values of the consistency *K* and the sensibility *m* of the Norton-Hoff law comes from [13], and they are interpolated linearly with temperature as proposed by [4].
For the mechanical contact between the workpiece and the tool, the parameters $\psi$ and $\beta$ are not well defined in the literature. For this reason, $\psi$ has been taken equal to 0 to model a constant shear stress $\tau$ as proposed in [4].

*Table 1. Thermal properties [8].*

| | Tool | Material |
|---|---|---|
| **Mass density ( $Kg.m^{-3}$ )** | -0.2299 θ + 7802 | -0.2264 θ + 2816 |
| **Specific heat ( $J.Kg^{-1}.°C^{-1}$)** | 0.3135 θ + 477.1 | 0.8509 θ + 825.7 |
| **Conductivity ( $W.m^{-1}.°C^{-1}$)** | 0.0489 θ + 22.5 | 0.1265 θ + 153.4 |

The thermal properties are described in Tab. 1. For the convective heat flux exchanged with air (20°C), *Chao and Qi* [14] have proposed to use a convective heat transfer coefficient $H_{ext}$ equal to 30 $W.m^{-2}.K^{-1}$ at the top surface of the workpiece. For the modelling of the contact between the bottom surface and the backing plate (100°C), this coefficient has been taken equal to 200 $W.m^{-2}.K^{-1}$.
In this example, the welding is performed for butt welding of 100mm*8,128mm*400mm plates using a tool having a 25,4 mm shoulder diameter, 100mm pin diameter, and 8mm pin length as proposed in [2]. The plates are welded at a welding speed of 60 $mm.min^{-1}$ and a rotational speed of 900 $rev.min^{-1}$.

Fig. 5 gives a comparison of the velocity profiles on upper surface obtained for two values of the shear stress $\tau = \beta.K$ : 20 Mpa and 40 Mpa. These calculations shows the influence of the mechanical contact conditions on the velocity fields [4]. For $\tau$ equal to 20 Mpa, the temperature profile is plotted in Fig. 6. In this case, streamlines are shown in Fig. 7. All these results are not compared to experimental measurements. It should be interesting to develop an inverse approach with experiments to model the tool-material contact conditions as described in the literature [15] to estimate the shear stress in a global approach.

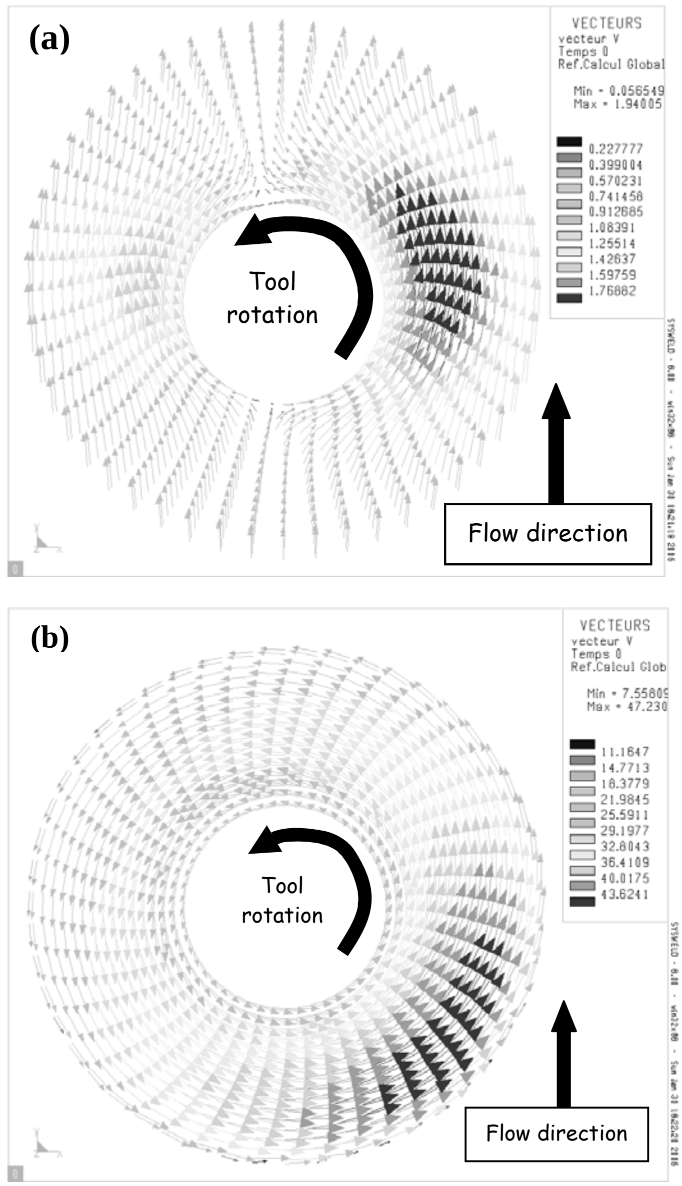


*Figure 3: Velocity profiles ($mm.s^{-1}$) on upper surface for two values of the shear stress $\tau$: 20 MPa (a) and 40 MPa (b).*

## Conclusion

The future objective of this work is to develop a numerical model to simulate the residual stresses and the distortions in Friction Stir Welding. In this paper, a 3D finite element procedure is presented to model the thermofluid flow in FSW for the stationary step in SYSWELD®. For each calculation composed of a mesh containing about 8000 nodes, the CPU time is less than half an hour on a single PC computer.

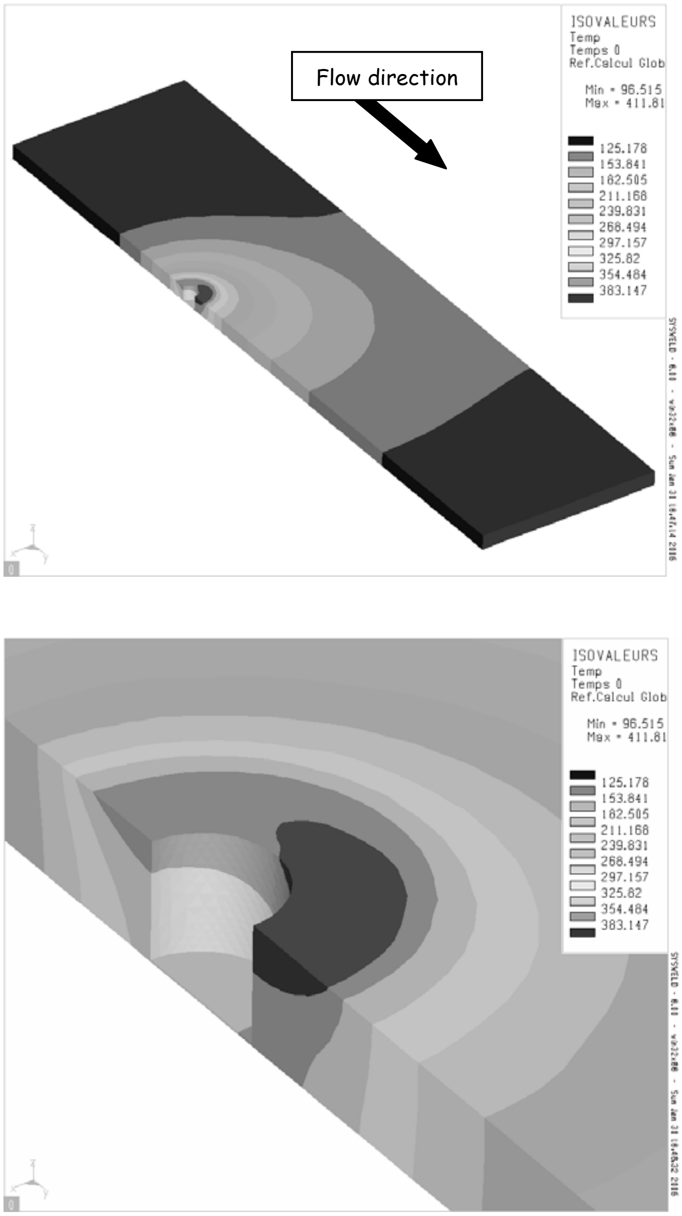


*Figure 4: Temperature profile (°C) for a shear stress $\tau$ of 20MPa.*

In the example presented above, there are some physical considerations which are not carefully taken into account. For example, the mechanical contact conditions are modelled with a constant shear stress which is most probably temperature dependent. This should leads to a better prediction of the temperature profile. Moreover, the thermal field can be affected by the modelling of the heat dissipated at the interface between the tool and the material which is modelled without considering the exchanged heat flux. It should also be interesting to take account of the thermal contact conditions between the material and the backing plate in a complete 3D model [4].

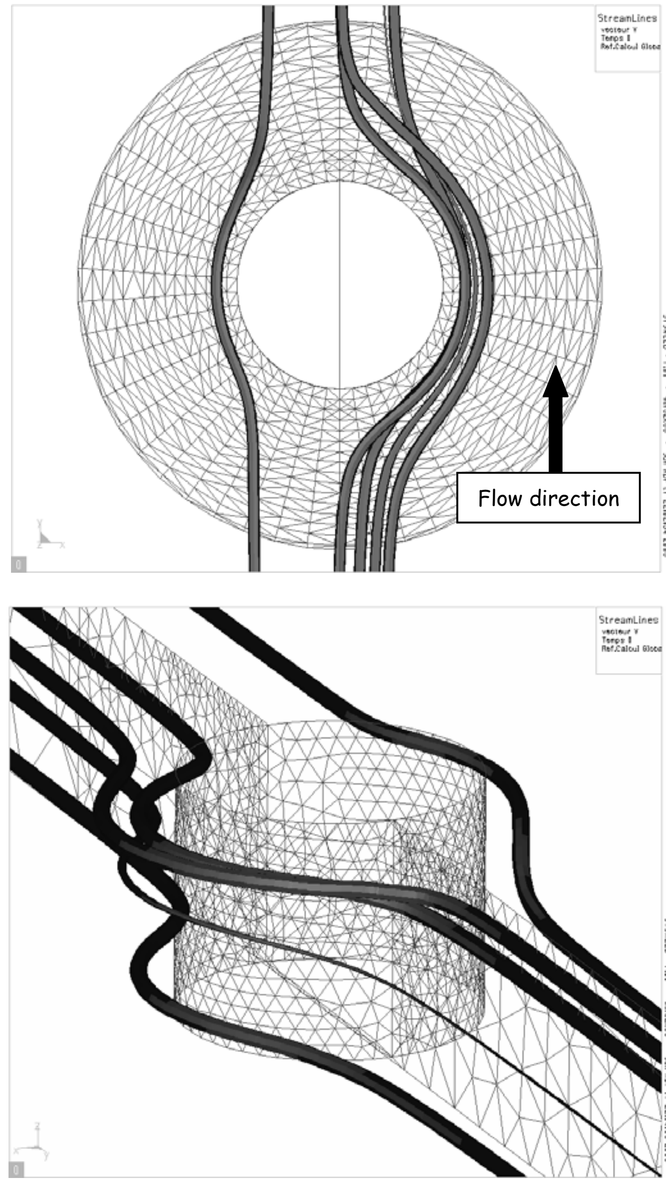


*Figure 5: Streamlines for a shear stress of 20 MPa.*

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