Simplified simulation of the friction Stir Welding Process. Influence of the boundary conditions modelling
Christophe Desrayaud

To cite this version:

HAL Id: hal-00854311
https://hal.science/hal-00854311
Submitted on 23 Jun 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License
**Simplified simulation of the friction Stir Welding Process.**
**Influence of the boundary conditions modelling.**

Christophe DESRAYAUD $^{1,a}$

$^1$ Ecole Nationale Supérieure des Mines de Saint-Etienne. Laboratoire Claude Goux UMR CNRS 5146. 158, Cours Fauriel 42 023 Saint-Etienne, France

$^a$ Email : cdesray@emse.fr

**Keywords:** Friction Stir welding, thermomechanical modelling, rheology, boundary conditions.

**Abstract.** A simple three dimensional thermomechanical model for FSW is used in the present paper. It is developed from the model proposed by Heurtier[1] improved by Jacquin [10] to account for the eulerian cooling flux due to the tool motion during welding. The velocity fields used to describe the bulk flow around the tool are introduced in the particular derivative of the thermal equilibrium equation. The complete thermomechanical history of the material during the process can then be accessed by temperature and strain rate contours.

A specific attention is given to the boundary conditions of the model:

- The choice of a quadratic interpolation of the temperature field in the vicinity of the surfaces subjected to thermal exchange with the tools enables to prevent the accuracy loss classically observed with coarse meshes.
- The modelling assumptions to account for tribological phenomena are discussed according to amount of sliding calculated by the model between the tool and the surface of the welded sheet.
- Finally the model provides a global balance of the power dissipation by means of the eulerian flux due to the tool motion or exchanges with the tools.

Analyses of the results obtained with the present model provide information on the global behaviour during welding and on the tendencies expected when modifying the operating parameters.

**Introduction.** Friction Stir Welding (FSW) is a solid state joining process, which is currently being developed for difficult-to-weld high strength aluminum alloys (e.g. the 2xxx and 7xxx series). It was developed and patented by The Welding Institute (TWI) in 1991. A hard cylindrical tool with a threaded pin and a shoulder rotates and slowly plunges into the joint line between two workpieces butted together. Friction and Stirring generate heat dissipation so that the workpieces soften without reaching the melting point. The material is plastically deformed and transferred from the leading edge to the trailing edge of the tool, leaving a solid phase bond between the two pieces when the tool is moved along the joint line.

Generally, two types of modeling techniques are reported in the literature according to the thermomechanical point of view. Each of them leads to the resolution of strongly non linear systems detailed in the next section a recent review on simplified modeling is proposed by [1].

**Fluid formulations.** The fluid formulation simulates the flow of the material around the tool in the steady state. These models are eulerian models and based on the linear momentum conservation equation written as follows:

\[
\text{div}(\bar{S}) - g \bar{f} \text{ad} (P) + \bar{f} = \rho \left( \frac{\partial \bar{v}}{\partial t} + \bar{v} \cdot g \text{ad} (\bar{v}) \right)
\]  

(equation 1)

where $\bar{S}$ is the deviatoric stress tensor, $\bar{f}$ the volume forces, $P$ the hydrostatic pressure, $\rho$ the density and $\bar{v}$ the velocity field. Reynolds [3] developed models in which the rheological behavior is considered as a function of instantaneous temperature and strain rate (Sellars and
The velocity field is the nodal mechanical variable to be solved in the problem. It must be noted that equation 1 can be developed in the case of a Newtonian liquid to obtain the classic Navier-Stokes equation. Considering the flow rule of metallic alloys at high temperature the choice of a non linear behaviour is recommended in the generic form:

$$
\tilde{S} = \frac{2}{3} \tilde{\sigma} \tilde{e}^{\text{plastic}} = 2 \mu \tilde{\epsilon} \tilde{e}^{\text{plastic}}
$$

(equation 2)

Where $\tilde{\sigma} = f(\tilde{\epsilon}, T)$ is the equivalent plastic Von Mises flow stress, and $\tilde{\epsilon}$ the Equivalent Von Mises strain rate and $\tilde{e}^{\text{plastic}} = \frac{1}{2}(\text{grad}(\tilde{\epsilon}) + \text{grad}^T(\tilde{\epsilon}))$ the plastic strain rate tensor. $\mu = \frac{\tilde{\sigma}}{3\tilde{\epsilon}}$ is the temperature and strain rate sensitive viscosity of the material (Ulyssé[3]). Introducing equation 2 in equation 1 leads to:

$$
d\tilde{\epsilon} \left( \frac{2}{3} \tilde{\sigma} \tilde{\epsilon}^{\text{plastic}} \right) - \tilde{\epsilon} \text{grad}(P) + \tilde{\epsilon} = \rho \tilde{\epsilon} \text{grad}(\tilde{\epsilon})
$$

(equation 3)

A strong nonlinearity appears in the second left hand term, actually $\tilde{\epsilon}$ is a function of the velocity, nodal variable of the problem. It must be solved iteratively, by FEM for example.

For the contact boundary conditions, the fluid formulation generally requires an imposed velocity field. Collegegrove [6] assumes that the material is completely sticking to the tool. Heurtier [2], Elangovan [7] and Ulyssé [5] suggested to distinguish the contact with the shoulder considered as sticking or partially sliding, and the contact with the pin that is assumed to be perfectly sliding circumferentially. As a consequence a vertical velocity is prescribed along the pin to account for the vertical dragging by the filet at a velocity value equal to the product of the tool rotational speed and the thread pitch: $V_{rot} L_f$ as suggested by Colligan [8]. Note that sliding contacts can be treated by introducing a contact law, increasing consequently the d.o.f. number of the problem. The switch between sticking and sliding cannot be treated in such formulations because no elastic stress is available. Dependence of the shear stress to Von Mises equivalent stress can be established with the definition of $\overline{m}$ the “Tresca” friction coefficient (Jacquin [10]). This technique is well adapted for the contact with the rotating tool.

**Solid formulations.** The solid formulation are lagrangian formulations and based on the linear momentum equation written as follows:

$$
d\tilde{\epsilon} \text{div} (\tilde{\sigma}) + \tilde{f} = \rho \frac{\partial \tilde{\epsilon}}{\partial t}
$$

(equation 4)

where $\tilde{\sigma}$ is the elastic stress tensor, $\tilde{f}$ the volume forces, $\rho$ the density and $\tilde{\epsilon}$ the velocity field. This formulation involves elastic stresses, calculated thanks to the displacement nodal values. In this case the plastic flow stress may depend on temperature, strain rate and thermomechanical history (i.e. hardening or softening) and includes a strong nonlinearity. Classic plasticity algorithms are used, based on the elastic estimator and the radial return technique. Implicit finite element solving requires the calculation of the elasto-visco-plastic tangent matrix. Furthermore, a geometric nonlinearity is to be considered and treated by means of an actualization of the configuration at each increment of iteration during the calculation. Note that for the solid (lagrangian) formulations, remeshing or mesh adaptations are required, during which, strain, strain rate and temperatures are interpolated between the old and new grid.

The solid formulation allows to implement the contact behavior with either Coulomb or “Coulomb limited by Tresca” [4] laws. The switch between sliding and sticking contact can be treated. An additional nonlinearity appears due to the nodal reactions of contacting zones between the welded material and the tools.
To summarize, both of the modeling techniques involve non linear phenomena belonging to the three classic types: geometric, material or contact nonlinearity. Furthermore, the high gradient values of the state variables near to the probe and the thermomechanical coupling implies a large number of degrees of freedom in FSW modeling, which appear to be cost full in CPU time: several hours calculations are classically required for one test case convergence.

**Simplification of the thermomechanical modeling of the FSW process.** This paper presents a model based on a eulerian thermal calculation, the convection term of which uses the velocity fields proposed by Heurtier to describe the material flow around the tool. The plastic power dissipated through plastic straining is estimated by means of a strain rate and temperature sensitive flow rule including a strong nonlinearity with respect to the temperature variable. This nonlinearity requires the use of a “flow rule” tangent value actualized at each iteration of the global calculation.

![Figure 1: Partitions of the welding zone for the elementary velocity field definition.](image)

**Thermo-mechanical model used in the present paper.** As described above the present model derives from the formulation proposed by Heurtier to describe the material flow around the tool during the welding operation. The welding zone is partitioned in tree sites (figure 1) to define the flow arm zone (1) for the torsion velocity field, the stirring zone (2) for the “vortex like” velocity field and rest of sheet (3) and the first two zones for the circumventive velocity field. The thermal equation is then solved accounting for the particular derivative terms containing the whole velocity field of the material flowing around the tool when welding occurs.

This model is clearly described by Jacquin [10] and leads to relevant results in terms of temperature contour presented on the figure 2 for a 2024 Aluminium alloy 3.2 mm thick. In the present paper, a slight modification was brought to the interpolation of temperature field in the vicinity of the surface where thermal exchanges occur according to the classic expression:

\[
\lambda \frac{\partial T}{\partial \vec{n}_i} = H_i \left( T_i - T_{\text{sink}} \right)
\]

(equation 5)

with \( \vec{n}_i \) normal to the surface \( i \), \( H_i \) exchange coefficient across the surface \( i \) bathing in a liquid at a sink temperature (far from the surface) \( T_{\text{sink}} \).
In the vicinity of the tool, a quadratic interpolation of the temperature gradient, normal to the face, allows to reduce the mesh refinement required to prevent accuracy loss on the temperature values obtained at the nodes. Note that the loss of accuracy on the flux values still stands because of the size of the mesh. Nevertheless, as shown on the figure 2, the eulerian cooling flux is well captured by the simulations. As the tool motion increases the temperature values decreases (maximum, minimum and average) temperature values of the whole model.

**Balance between relative sliding and plastie deformation in the bulk.** Information on the power breakdown between a surfacic and volumic part is also available. Indeed an additional procedure was inserted to account for eventual sliding between the shoulder and the matter subjected to the weld. This variation was studied as a function of the tool rotative velocity (keeping the tool motion constant) and as a fuction of the tool motion (keeping the rotative velocity constant). Results are synthesised on the figure 3 out of Jacquin et Al [10]
Figure 3: Breakdown of the power between surfacic dissipation (relative sliding due to friction) and volumic dissipation (plasticity) Jacquin [12].

It can be seen that a good agreement, analysed by Jacquin [10], is founded with experimental measurements. As the welding velocity increases an equilibrated balance establishes between the surfacic and volumic dissipated power. Note that, as the tool motion increases the average temperature in the weld decreases; The shear stress required to develop the flow arm zone increases significantly and promotes thus the relative sliding between the tool and the surface. Although the dissipated plastic power decreases in the early range of tool motion the total power increases on the whole considered range because of the temperature sensitivity of the material affecting the plastic flow stress and the shearing stress in the contact (Tresca behaviour).

Global power balance. The present model provides the facility to achieve a balance on the whole power loss of the welding zone integrating the thermal exchanges with the tool and atmosphere and the heat convected by the welded matter flowing around the tool. This eulerian flow justify the decrease of the average temperature when the tool motion increases. The global power balance is written for the present model as follows:

\[
\int_{V} \sigma \varepsilon \, dV + \int_{S} \tau \Delta \hat{u} \, dS - \int_{S} \hat{\Phi} \cdot \hat{n} \, dS = \int_{V} \rho_c \dot{T} \, dV
\]  
(equation 6)

and can be developed as follows if steady state is considered:

\[
\int_{V} \sigma \varepsilon \, dV + \int_{S} \tau \Delta \hat{u} \, dS - \int_{S} \hat{\Phi} \cdot \hat{n} \, dS - \int_{S} \rho_c \cdot \dot{T} \cdot \hat{n} \, dS = 0
\]  
(equation 7)

The first, second and third left hand terms are classic and represent respectively the plastic deformation friction (relative sliding) power and the power lost by means of heat fluxes outside the integration volume. The third term (thermal exchanges with the tool and atmosphere) is generally negative because the temperature values in the volume are higher than the sinking temperature associated to the flux exchange coefficients. The fourth term of the model represents the eulerian power loss (power transported across the surface of the model by the material flow). This term is also negative because the material entering in the volume is generally colder than the material exiting the model at the opposite side. The absolute value of this term strongly depends on the welding speed. Finally the right hand term in equation 6, highlights the significance of the average temperature directly affected by changes in the power balance. At steady state the right hand terms balance so that the variation of the average temperature is zero and can be written as
The figure 4 illustrates the route of the heat out of the welding zone. The heating power is generated in the vicinity of the tool by volumic and surfacic power and extracted by conduction (with the tool or atmosphere) and convection loss by the material flow.

![Figure 2: Break down of the power dissipated into convection and conduction effects.]

At low value of the tool motion the eulerian loss is weak and the main part of the plastic power is diffused by outward conduction exchange. Nevertheless the global power loss will be weak and the mean temperature may increase. At high values of the tool motion, the main part of the motorisation power is evacuated by the transport phenomenon. It is clearly known experimentally that a compromise has to be found on the temperature of the weld that could be quantified by the mean temperature of the weld. Although the absolute value of the mean temperature is to be considered carefully (because depending on the size of the model) the tendencies presented on the mean temperature value would always stand if changing the limit size.

**Conclusion.** The model used in the present paper due to its simplified assumptions offers facilities to understand the behaviour of the welding zone according to the chosen operating parameters. The breakdown of the power dissipated into volumic and surfacic part clearly highlights the limits of the range in which the rotative velocity of the tool is to be chosen. Moreover the eulerian formulation enables to capture the cooling effect due to bulk material flow around the tool and explains the monotonic increase of power dissipation with the tool motion. Finally the model offers a description of the route for heat extraction through the tool and backing bar or by means of convection due to the tool motion. This analysis gives a formal justification to the choice made practically for the tool motion and the rotative velocity of the tool by quantifying the risks on the extreme temperature or torque values.

**References**