The Overview of Modeling the Thermo-Mechanical Three Dimensional Friction Stir Welding Process

Meiling Jiang ¹,²,a , Min Wang ¹,b  
Dong Chen ¹,²,³,c

¹Shenyang Institute of Automation, Shenyang, Liaoning Province, China  
²Graduate School of the Chinese Academy of Sciences, Beijing, China  
³Liaoning University of Science and Technology, Anshan, Liaoning Province, China

Keywords: Friction Stir Welding; Thermo-Mechanical Model; Finite Element Method

Abstract. A three dimensional thermo-mechanical model for FSW is presented. It's based on the model proposed by Alma H. Oliphant et al.[1] and Jacquin, D.et al.[2]. Velocity fields and initial plunge temperature profile are introduced in the steady state calculation of the temperature field during welding. And the non-adiabatic heat transfer conditions between the tool, the work piece, and the backing plate are also applied to the model. So a more accurate temperature will be got. It is anticipated that the model can be extended to optimize the FSW process parameters.

Introduction

Friction Stir Welding(FSW) is a relatively new and promising solid-state joining process originally developed primarily for aluminum alloys in 1991 by The Welding Institute(TWI), in Cambridge, UK[1]. FSW has various advantages over traditional fusion welding techniques such as its lower costs, environment friendly, moderate distortion, and versatile.

The basic concept of FSW is related to a non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint (Fig. 1).

Fig.1 Schematic of friction stir welding

FSW control applications are subject to many significant process variables such as rotational speed, traverse speed, axial force, plunge depth of pin and shoulder, geometry of tool and work-piece, torque and the field of temperature. In addition FSW process is a coupled thermo-mechanical solid-state process. This process presents a formidable challenge to researchers attempting to characterize this event through various modeling techniques.
Askari et al[3] used CTH, a Sandia National Labs produced hydrocode, to capture the coupling between tool geometry, heat generation, and plastic flow of the material in their three dimensional model. Bendzsak et al[4] also model the FSW process in three dimensions, however they assume the material to be a fluid, with a viscosity equal to that of the material at the eutectic temperature. Various models are available for the contact boundary conditions. Colegrove and Shercliff (2005) assume that the material is completely sticking to the tool. Schmidt and Hattel (2005) study the effect of sticking vs sliding or partially sticking conditions at the tool/workpiece interface on the temperature field. Ulysse[5], Heurtier et al. (2006) and Bastier et al. (2008) distinguish between 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.

Thermo-mechanical model description

2.1 Initial condition
At the beginning of a general simulation the temperature is set on entire mesh with 20°C same as the room temperature. However the actual process begins with about 7s plunge and 12s preheat process. In order to make the simulation fit the FSW process better we inlet the temperature profiles of the plunge process through experiment.

2.2 Thermal calculation
the thermal differential equation is carried out over the volume of the workpiece based on Fourier's equation. An Eulerian steady state formulation is chosen resulting the following energy balance:

\[
\frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + \Gamma_d \dot{\sigma}_0 \dot{\varepsilon} + Q_i = \rho c \left( \frac{\partial T}{\partial t} + V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} + V_z \frac{\partial T}{\partial z} \right)
\]

(1)

Where \(\lambda\) is the thermal conductivity (W/(m·K)), \(T\) is the temperature (K or °C), \(\Gamma_d = 0.90\) is the Taylor-Quinney parameter accounting for the fact that a small part of the energy is stored in the material in the form of defects. \(\sigma_0\) is the flow stress, \(\dot{\varepsilon}\) is the equivalent von Mises plastic strain rate, \(Q_i\) is the internal heat sources generated by the pin (KJ/m²), \(\rho\) is the material density (kg/m³) and \(c\) is the specific heat (J/(kg·K)). The particular derivative term (right hand term) and the strain rate (second left hand term) are calculated through the global velocity field \(\vec{V}\) describing the material flow around the tool. The second part in the left of the equation \(\dot{W}_{vol} = \Gamma_d \dot{\sigma}_0 \dot{\varepsilon}\) is the dissipated power density of rheology of the welded material.

The flow stress \(\sigma_0\) is assumed to be equal to a power viscoplastic Arrhénius law, with non-linear strain rate sensitivity.

\[
\sigma_0 = K \dot{\varepsilon}^m e^{mQ/RT}
\]

(2)

Where \(K\) is the "viscosity like" parameter and is set to 1.5(MPa·s\(^m\)), \(m\) is the strain rate sensitivity, \(Q\) is the activation energy of the material flow (kJ/mol),
The Fourier's equation:

\[ q^* = -\lambda_{nn} \frac{\partial T}{\partial n} \]  

(3)

In the equation \( q^* \) -- the heat flow density\( (W/ m^2) \)
\( \lambda_{nn} \)--thermal conductivity\( [W/(m \cdot K)] \)

2.3 Heat generation calculation

The rate of heat generation at the interface between the shoulder and the top of the workpiece surface is a function of the coefficient of friction \( \mu \), angular velocity \( \omega \), and radius \( r \). The density of heat flow produced by the shoulder according to reference[7]:

\[ q(r) = \tau \omega r \quad (R_p < r < R_s) \]  

(4)

Frictional Contact Algorithms

\[ \tau = -\alpha \cdot K(T, \bar{\varepsilon}) \cdot V^{p-1} \cdot V \]  

(5)

Here \( \tau \) is the frictional shear stress, \( \alpha \) is the coefficient of friction, \( p \) is the sensitivity to sliding, \( V \) is the difference in velocity between the two surfaces, \( T \) is temperature, and \( \varepsilon \) is strain tensor. The default values of 0.3 and 0.15 were used for \( \alpha \) and \( p \) respectively. The surface of the backing plate was tied to the bottom surface of the weld material, and not allowed to slip.

In the model the pin is considered to be a internal volume heat source:

\[ Q_i = \tau_s \omega \]  

(6)

Where \( \tau_s = 0.577 \sigma_{0.2} (T) \), \( \sigma_{0.2} \) is the material yield limitation.

2.4 Thermal boundary condition

Here we utilize a non-adiabatic heat transfer condition between the tool, the work piece, and the backing plate. Fig 2 also defines the surfaces of the model represented by a hollow cylinder where the internal surface corresponds to the pin and the bottom surface is set on the backing plate. So we apply the convection boundary condition to the model:

\[ \lambda \frac{\partial T}{\partial n} = h_f (T_{surf} - T_{surr}) \]  

(7)

For air cooling the exchange coefficient \( h_f=30 \text{ W/m}^2\text{°C} \), the backing plate cooling \( h_f=200 \text{ W/m}^2\text{°C} \), the temperature of the plate is set to 100°C according to the value optimized by Feulvarch et al.(2005).

A approximation for the radiation from the tool can be made by:

\[ Q = \varepsilon \sigma A_s (T_{surf}^4 - T_{surr}^4) \]  

(8)

where \( Q \) is the energy\( (W) \), \( A_s \) is the surface area, \( \varepsilon \) is the emissivity of the surface, \( \sigma \) is the Stefan Boltzmann constant \( (5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4) \), \( T_{surf} \) is the surface temperature, and \( T_{surr} \) is the surrounding temperature which is set to 20°C.
2.5 Mechanical boundary condition

The model in this paper considers the sliding phenomenon between the shoulder and the workpiece. The phenomenon implies a surface power dissipation:

\[ Q_s = \frac{\bar{m}}{\sqrt{3}} \sigma_0 V_s \]  

(9)

The \( \bar{m} \) chosen for the friction coefficient is 0.45, \( V_s = V_{tool} - V_{surf} \) is the sliding velocity.

The surface velocity can be expressed as

\[ V_s = \frac{h}{r_m} \dot{\varepsilon}_m \]  

(10)

In this model the height of the flow arm zone1 (fig2) is \( 1.27 \text{mm} \), \( r_m = (R_s + R_p)/2 \), \( \dot{\varepsilon}_m \) is the mean strain rate in the vicinity of the probe. Some researcher’s computation has shown that about 70% of the surface power density is transferred into the bulk of the workpiece.

Numerical implementation

3.1 materials data

Table 1 shows the geometry parameters and the material of the tool and Table 2 presents the property of base material alloy A7075-T651.

| Tilt angle | Pin diameter | Pin height | Pin shape | Shoulder diameter | Tool material |
|------------|--------------|------------|-----------|-------------------|---------------|
| 0          | 8mm          | 6.35mm     | Cylindrical, flat pin end | 25.4mm         | Rust resisting steel |

Table 2 characteristics of the workpiece A7075-T651

| Density \( \rho [\text{kg/m}^3] \) | Yield limit \([\text{Mpa} @ 25^\circ\text{C}] \) | Maximum shear stress \([\text{Mpa}] \) | Specific heat \([\text{J/(kg-K)}] \) |
|-----------------------------------|---------------------------------|-------------------------------|-----------------|
| 2.82                              | 505                             | 152                           | 900             |

3.2 Finite element model

In modeling the temperature history, the moving heat sources of the shoulder and the probe are presented as moving the heat generation of the nodes in each computational time step. The mechanical effect by the shoulder is involved in the mechanical model, as the relatively larger contact region of the shoulder and the workpiece is expected to contribute a large part of the mechanical stress, especially in the up-half part of the weld. The temperature gradient is large around the welding zone and seriously changes the materials properties. In order to increase the accuracy of the mechanical solution, the thermal and mechanical solutions are coupled: the temperature data at each increment time is used to evaluate the mechanical properties and the thermal parameters.
Conclusions

Based on the above prescribed model the finite element Analysis software ANSYS is used to implement the simulation. Though the model needs a great deal of simulation and experimental datas, it can fit the actual welding process better. Therefore the result can be a more promising reference to adjust the welding process parameters.

References

[1] Alma H. Oliphant, numerical modeling of friction stir welding: a comparison of ALEGRA and FORGE3. A thesis submitted to the faculty of Brigham Young University. August 2004. pp. 57-58.

[2] Jacquin, D. et al. A simple Eulerian thermomechanical modeling of friction stir welding. Journal of Materials Processing Technology In Press, Corrected Proof, doi:DOI: 10.1016/j.jmatprotec.2010.08.016.

[3] Askari, A., Silling S., London, B., Mahoney, M. Modeling and Analysis of Friction Stir Welding Processes. 4th International Symposium on Friction Stir Welding. Park City, UT. May 2003.

[4] Bendzsak, G., North, T., Smith, C., An Experimentally Validated 3D Model for Friction Stir Welding. Proceedings of the 2nd International Symposium on Friction Stir Welding. Gothenburg Sweden. June 2000.

[5] Ulysse, P. Three-Dimensional Modeling of the Friction Stir Welding Process. International Journal of Machine Tools and Manufacture. Vol. 42. pp. 1549-1557. 2002.

[6] Zhao Yan-hua, Lin San-bao, Wu lin, He zi-qiu. A review of material flow simulation during friction stir welding. Vol.35(8),2005

[7] Zhang Yan-fu, Ke Liming, Sun De-chao. The distribution of Temperature and Material Flow of Friction Stir Welding. Journal of Nanchang institute of aeronautical technology (natural sciences). vol.17(3),2003.

[8] Smith SD. A review of models for simulation of material flow during friction stir welding[P]. United Kindom:775/2003.