NUMERICAL SOLUTION OF FRICTION STIR WELDING USING SYSWELD

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Abstract Friction Stir Welding (FSW) is one of the most effective solid state joining processes and has numerous potential applications in many industries. The simulation process can provide the evolution of physical quantities such as temperature, metallurgical phase proportions, stress and strain, which can be easily measured during welding. The numerical modeling requires the modeling of complex interaction between thermal, metallurgical and mechanical phenomena. The aim of this paper is to describe the thermal-fluid simulation of FSW using the finite element method. In the theoretical part of the paper is heating provided by the material flow and contact condition between the tool and the welded material. Thermal-fluid and thermo-mechanical results from numerical simulation using SYSWELD are presented for aluminum alloy.

1 INTRODUCTION

Friction stir welding (FSW) is a relatively new joining technology which was developed and patented in 1991 by The Welding Institute (TWI), United Kingdom [1]. This is a solid-state welding process providing good quality of butt and lap joints. The FSW process has been proven to be ideal for creating high quality welds in a number of materials including those which are extremely difficult to weld by conventional fusion welding. A schematic of friction stir welding process is illustrated in Fig. 1.

Figure 1: Schematic diagram of FSW.

The welding zone is completely isolated from the atmosphere during the welding process. One of the advantages of this type of welding is minimized formation of voids in the welding

zone, so that welding defect and large distortion commonly associated with fusion welding are minimized or avoided. This welding technique is extensively applied to the aerospace, automobile and shipbuilding industries [4, 5, 6, 7, 8].

2 THEORETICAL BACKGROUND

In FSW, the heat generation takes place mainly under the shoulder, leading to variable thermal gradient in the through-thickness direction of the plate. The general three dimensional partial differential equation of heat conduction in solid can be represented by

$$\frac{\partial(\rho c T)}{\partial t} = \frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) + \frac{q_o}{V}, \quad (1)$$

where ρc is the volume heat capacity; x , y and z are the space coordinates; k_x , k_y and k_z are thermal conductivity, T temperature, t time and q_o/V .

2.1 Heat generation during FSW

For the ideal case considered in Fig.1, the torque required to rotate a circular shaft relative to the plate surface under the action of an axial load is given by [2]

$$M = \int_0^R dM = \int_0^R \mu P(r) 2\pi r^2 dr = \frac{2}{3} \mu \pi P R^3, \quad (2)$$

where M is the interfacial torque, μ is the friction coefficient, R is the surface radius, and $P(r)$ is the pressure distribution across the interface. If all the shearing work at the interface is converted into frictional heat, the average heat input per area and time becomes [2]

$$q_o = \int_0^R \omega dM = \int_0^R \square, \quad (3)$$

where q_o is the net power (in Watts) and ω is the angular velocity (in rad/s). Angular velocity can be expressed in terms of the rotation speed N . By substituting $\omega = 2\pi N$ into Eq. (3), we get

$$q_o = \int_0^R 4\pi^2 \mu P N r^2 dr = \frac{4}{3} \pi^2 \mu P N R^3. \quad (4)$$

From Eq. (4), it is obvious that the heat input depends both on the applied rotational speed and the shoulder radius, leading to a nonuniform heat generation during welding.

2.2 Heat generation in SYSWELD by FSW modulus

In SYSWELD by FSW modulus is effective viscosity μ defined from Newton-Hoff law used to model hot forming process [3]:

$$\mu = K(T) \cdot (\sqrt{3} \cdot D)^{m(T)-1}, \quad (5)$$

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

$$D = \sqrt{\frac{2}{3} \bar{D} : \bar{D}}, \quad \text{where} \quad \bar{D} = \frac{1}{2} (\text{grad}(\vec{v}) + \text{grad}^T(\vec{v})). \quad (6)$$

The friction between the toll and the work piece is of Neumann boundary condition. Heat flux density modeled between tool and material contact is [3]

$$q = \beta \cdot \vec{\tau} \cdot \Delta \vec{v} \quad (7)$$

where β is the proportion of the heat dissipated thought viscous dissipation $\vec{\tau} \cdot \Delta \vec{v}$ and received by the sheets. All thermal boundary conditions are in the Fig. 2.

Figure 2: Thermal boundary conditions.

3 NUMERICAL SOLUTION BY SYSWELD

An example is presented in this section. The first step of the solution is the thermo-fluid analysis. The thermal properties for the sheet and backing plate are described in Tab. 1, friction coefficient is 0.238, linear welding velocity is 1.00 mm/s, tool rotation velocity 41.89 rad.s, room temperature 15°C, and the heat exchange coefficient for convection 19 W/(m.K). In Fig. 3 a finite element model of sheet and backing plate for thermo-fluid analysis is presented. In Fig. 4 a finite element model of the tool is shown. In Fig. 5 a model for thermo-mechanical model and material properties are described in Tab. 1. In fig. 6 and 7 the result of the solution with the SYSWELD® software is presented.

Figure 3: Thermal-fluid model for finite element analysis.

Figure 4: Finite element model of surface of tool.

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Temperature field is from thermo-fluid analysis.

Figure 5: Thermal-mechanical model with boundary conditions.

Table 1: Material properties of sheet and backing plate.

T (°C)	SHEET (Aluminum alloy)						BACKING PLATE (steel)		
	k $\left(\frac{W}{mm^{\circ}C}\right)$	$\rho \cdot 10^{-6}$ $\left(\frac{kg}{mm^3}\right)$	C $\left(\frac{J}{kg^{\circ}C}\right)$	E (GPa)	η (-)	α	k $\left(\frac{W}{mm^{\circ}C}\right)$	$\rho \cdot 10^{-9}$ $\left(\frac{W}{mm^3}\right)$	C $\left(\frac{J}{kg^{\circ}C}\right)$
20	0.130	2.750	898.0	70.0	0.33	0.0125	0.068	7850	430
120		2.730	951.0	70.0	0.33				500
220		2.710	1003.0	61.0	0.33		0.059	7800	550
320		2.690	1055.0	55.6	0.33				580
420		2.660	1108.0	49.3	0.33		0.047	7730	610
500				41.3	0.33				650
587	0.170	2.630	1195.0	1.0	0.33				
600				1.0	0.33		0.036	7653	710
644		2.450	1200.0	1.0	0.33	0.0135			

700								7613	790
800							0.029		865
900							0.027		565
1450							0.033		
1600								7190	630
2477		2.230	1300.0						707

Figure 6: Temperature field at time 225 s of welding.

Figure 7: Von Mises stress at time 225 s of welding.

3 CONCLUSION

In this paper, 3D finite element procedures are presented to model the thermo-fluid flow and thermo-mechanical properties in FSW for the stationary step in SYSWELD®. For the computation of the example proposed in section 3, the mesh for thermo-fluid flow analysis is composed of 17892 nodes and 100191 elements in the Fig. 3 and the mesh for thermo-mechanical analysis is composed of 63261 nodes and 56000 elements in the Fig. 5. In Fig. 6 the temperature field at time 225 s from SYSWELD® is presented. In Fig. 7 the von Mises stress at time 225 s from SYSWELD® is presented. The numerical results were compared to experimental measurements with a thermo-camera, thermocouples and strain rosettes, which are in good agreement [2]. In section 2 a theoretical background is presented for the solution of FSW.

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