특 집 : 마찰교반용접

마찰교반용접 : 입열 계산

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Friction Stir Welding : Heat Input Calculation

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1. Introduction

A recent review stated that "an improved understanding of the mechanical properties of joints as a whole and the ability to control mechanical properties are much needed" before the process can be fully accepted by industry. In that sense FSW research have a far way to go.

In literature there are analytical model for stir zone (SZ) used for studying the heat transfer and residual stress in friction stir welded joint, but there are still some unsolved problems for the exact calculation of the size of the heat input zone and value of heat input.

If the prediction accuracy of the FSW thermal cycle is very low, it is impossible to predict the microstructure and properties in SZ thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) accurately and reliably. Welding heat input is the key factor influencing SZ behavior and the welding thermal cycle.

According to Askari[1] the heat generation due to plastic work is the dominating term during the steady state FSW process. In his model the friction force around the tool pin surface during steady state FSW process has been neglected as the material in this zone is plasticized and it under go plastic deformation rather than slip at the tool boundary. The model of FSW developed by William's[2] has been used as the base for the analytical model used in this study.

In this present study for FSW heat input in the SZ has three parts: Viscous dissipation transformed in to heat around the tool pin, plastic work around the tool pin converted to heat and work done by tool shoulder friction converted to heat.

2. Analytical Heat input model

In this present study shoulder zone and the vortex swirl zone are defined same as William's model. But the extrusion zone has been defined using more accurate geometry, as shown in model. The extrusion zone is classified as Advancing extrusion zone and retreating extrusion zone. These extrusion zones are again classified as Advancing upper and lower and Retreating upper and lower.

In order to get volume of heat input for Finite element analysis, the volume of the tool has been deducted from the total volume of the extrusion zone, shoulder zone and vortex swirl zone. The advancing upper and lower extrusion zone and Retreating lower extrusion zone has been defined using parabolic geometry and the Retreating upper extrusion zone by geometry as shown in Fig. 1. The die cavity volume has been deduced from volume of extrusion zone.

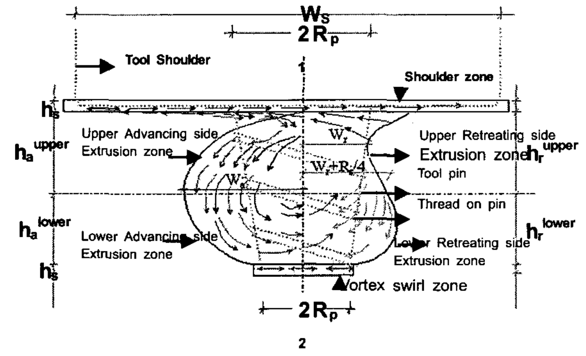

Fig 1. Schematics of metal flow pattern model of FSW and shape of the various sub zones in SZ

Based on the analytical model the width of retreating and advancing side were calculated. Using this value the radial distance of the boundary of heat input volume from the axis of the tool has been determined in both advancing and retreating side and the radial distance at the leading side was interpolated from these values at various level (along the thickness direction). Thus the three dimensional analytical model of the heat input volume has been created and based on which the finite element heat transfer analysis has been carried out and the thermal histories were determined. The details of the analytical model have been given in author's previous paper[3].

3. Heat input calculation

This paper is mainly concentrated on the heat input calculation in FSW. Types of heat source in FSW are viscous dissipation transformed in to heat around the tool pin, plastic work around the tool pin converted to heat and work done by tool shoulder friction converted to heat.

3.1 Viscous dissipation

Assuming that shear energy is completely converted in to heat

Rate of heat generated =Shear plane component of resultant force Shear Velocity*

Assuming that the heat source is uniformly distributed along the shear plane, heat source in Advancing side and Retreating side are given by equation 1 and 2 respectively.

$$q_{Sa} = \frac{(V_f + V_t) \times F_S}{W_a \times h_a} \tag{1}$$

$$q_{Sr} = \frac{(V_f - V_t) \times F_S}{W_r \times h_r} \tag{2}$$

3.2 Plastic deformation

According to Boothroyd the strain rate in the plastic deformed region varies linearly from the tool surface to stir zone boundary. The strain rate in the advancing side and retreating side are given by equation 3 and 4 respectively.

$$\dot{\varepsilon}_{pa} = \frac{(V_f + V_t)}{W_a} \tag{3}$$

$$\dot{\varepsilon}_{pr} = \frac{(V_f - V_t)}{W_r} \tag{4}$$

3.3 Friction Heat generated at interface

Heat is generated at the tool shoulder / matrix interface by friction. The intensity of the frictional heat source from shoulder in the advancing side and retreating side are given by equation 5 and 6 respectively.

$$q_{fa} = \frac{(V_f + V_t)F}{contact\,length} \tag{5}$$

$$q_{fr} = \frac{(V_f - V_t)F}{contact\;\;length} \tag{6}$$

4. Heat input calculation

To determine the thermal histories of the Friction Stir welding process the finite element heat transfer analysis has been carried out. The three dimensional FE model employed in this work is shown in the Fig. 2. The Solid brick element has been used for modeling and the total number of nodes and elements are 10010 and 8100 respectively. A sufficiently fine mesh at the stir zone, thermo-mechanically affected zone and heat-affected zone was generated to obtain more accurate results. The temperature dependent material of Al 6061-T6 has been used for the FE heat transfer analysis.

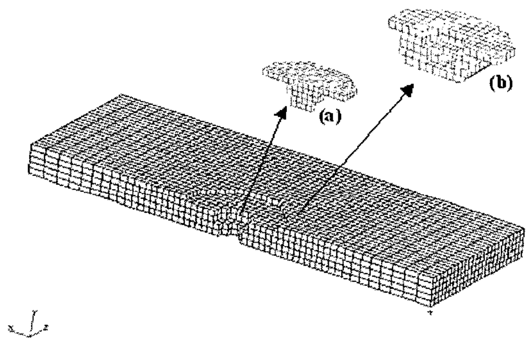

Fig. 2 3D FE model used for residual stress analysis of FSW; (a)- Elements at the die cavity; (b)- Elements around the die cavity (heat input elements)

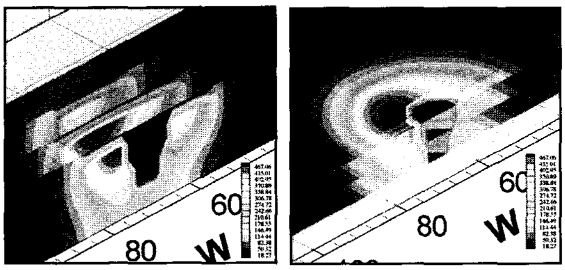

Fig. 3 Temperature distribution contour on the slice (a)-along the thickness (3mm, 6mm and 9 mm from the top) (b)-along the Length (0 mm, 6.67mm, 13.37mm and 20mm from the tool axis)

5. Results and Discussion

The three dimensional temperature distributions contour obtained from the FE heat transfer analysis has been shown in Fig. 3. In order to have a clear inside view of the 3D model, slice section along the length width and thickness has been plotted.

In order to compare these results with the experimentally measured value, the thermal distribution graph for depth of 3mm, 6mm and 9mm recorded at 4 locations in the advancing side and 4 along the retreating side and the values obtained are shown in Fig 4. and the corresponding numerically obtained value for time t =2.20 sec is shown in Fig. 5 and both the values are comparable.

6. Conclusion

The analytical model used for the heat input in the heat transfer analysis has been demonstrated for a particular tool geometry and material property. Based on this study following conclusions can be drawn.

1) The developed analytical model and the heat input calculation can be used to

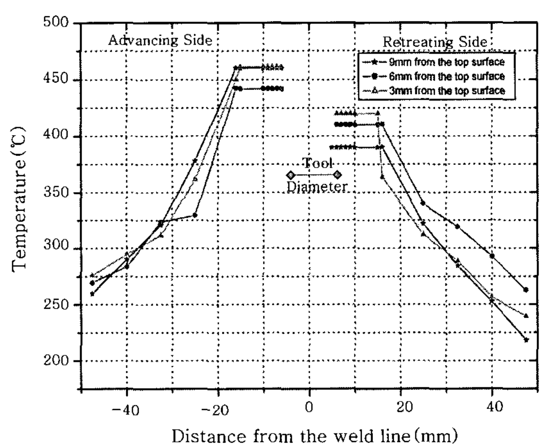

Fig. 4 Temperature distribution at various depths for FSW of 50-travel speed and 600-rotation speed measured using thermocouple

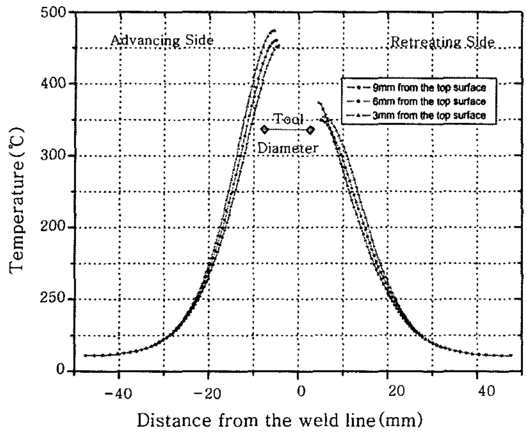

Fig. 5 Temperature distribution at various depths for FSW of 50-travel speed and 600-rotation speed obtained using the analytical model and non-linear heat transfer analysis. (at time, t=2.20sec)

accurately model the heat distribution along the uniform processing zone of FSW

2) The three-dimensional asymmetric heat distribution about the tool has been accurately modeled and experimentally validated.

Nomenclature

R_{p1}, R_{p2}	:	Radius of pin at top and bottom
R_s	:	Radius of shoulder
V_f	:	Forward travel speed
V_t	:	Pin tangential velocity = 2 R_p ◆
V_s	:	Velocity of material flowing in shoulder zone
◆	:	Rotation speed
h	:	Pin length
h_s	:	Depth of shoulder processing zone
h_a	:	Depth of advancing side extrusion zone
h_r	:	Depth of retreating side extrusion zone
●	:	Threads per inch
Ω^2	:	Projected thread area
W_a	:	Width of advancing extrusion zone
W_r	:	Width of retreating extrusion zone
W_s	:	Average width of shoulder zone
⁹Z	:	Distance material moves down per revolution
q_{Sa} , q_{Sr}	:	Rate of heat generated
F_S	:	Shear plane component of resultant force

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