특집 : 마찰 교반 접합

Transient Thermal Analysis of Friction Stir Welding using 3D-Analytical Model of Stir Zone

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Introduction

Friction Stir Welding is a solid state joining method with five phases of actions in its entire process. The first is the plunging period, where the pin is fully and shoulder is partially plunged into the joint line of the work piece. The second action is in the dwell period during which the tool keeps on rotating at the plunge point. In this phase the material around the tool is heated due to the friction between the probe and matrix surfaces due to sliding action. Due to this thermo-mechanical action, materials around the tool get plasticized. The third phase of action is in the steady state welding period, during which the rotating tool is traversed along the welding line. This is followed by a second dwell period, which is the fourth phase of action. The last and the fifth phase of action is in the releasing period during which the rotating tool is raised up from the weld line leaving behind a pin cavity in the work piece.

In the FSW model of William the metal flow zones are categorized as shoulder zone, extrusion zone and vortex swirl zone, and these zones are defined using regular geometries. 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 and based on Askari's concepts a combined analytical and finite element based model has been developed for thermal distribution analysis of FSW process and the thermal history in the Stir zone, Heat affected zone and the base metal has been determined.

Experimental Procedures

Work piece geometry and details.

The FSW setup consists of two 12mm thick Al6061 plates, 70mm wide and 100mm long. The plates are jointed such that the distance between the plunging point and the releasing point is 60mm. The tool is made of SKD-51 tool-steel, having shoulder height of 20mm and diameter of 32mm. The pin has a height of 9mm, upper and lower diameter of 11.56 and 8.30mm respectively.

Welding parameters.

FSW was performed at a rotation speed of 600 rpm and a welding speed of 50mm/min, tool-to-work piece angle was maintained at approximately 2.5° and an effective plunge depth of 9.12mm. At these values of the welding parameters an adequate welding quality was obtained.

Temperature measurement.

Three experiments were conducted at a travel speed of 50mm/min and 600 rpm varying the measuring depth to 3mm, 6mm and 9mm respectively. Each of this experiment the temperatures were recorded at 4 locations in the advancing side and 4 along the retreating side. The 1mm diameter holes were pre-drilled from the top surface of the plate and thermo couple of 1mm diameter were firmly fixed in to these holes after clamping the plate in the FSW machine. The temperature from the thermocouple is measured when the tool pin is between the starting

line and stopping line as shown in Fig. 1. The digital signals from the thermocouple were converted to thermals history graphs and database using the Labview package in the computer connected to the SC-2345 carrier.

Analytical model

In order to get the 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. 2.

The volume per unit time of the die cavity formation from Fig. 3 can be written as

$$V_{DC} = V_f (R_{p1} + R_{p2}) ht \tag{1}$$

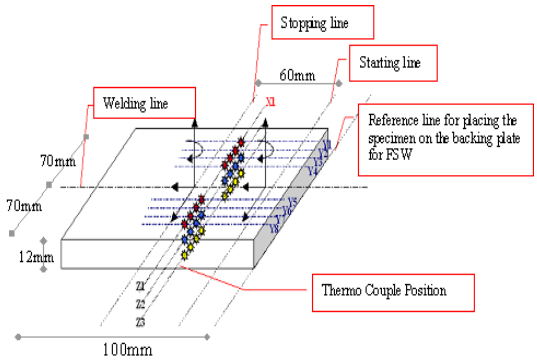

Fig. 1 Schematic of temperature measurement during FSW of Al6061

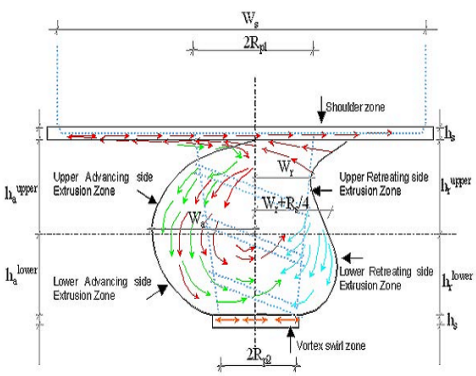

Fig. 2 Schematics of metal flow pattern model of FSW and shape of the various sub zones in SZ

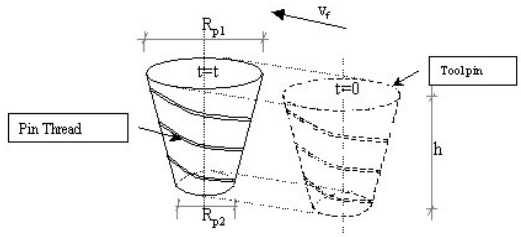

Fig. 3 The die cavity formation details of FSW pin

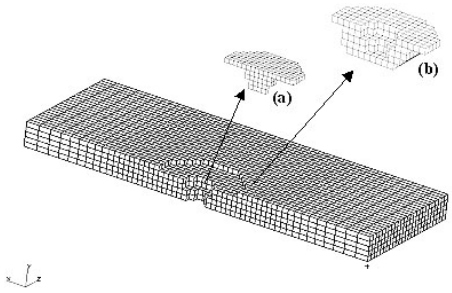

Fig. 4 Three Dimensional FE model used for residual stress analysis of FSW; (a) Elements at the die cavity; (b) Elements around the die cavity(heat input elements)

Volume of the material moving through the extrusion zone is given by

$$V^e = V^a + V^r \tag{2}$$

where V^a volume of the material moving through the Advancing side of extrusion zone

V^r volume of the material moving through the Retreating side of extrusion zone

Volume of the material moving through the Retreating side of extrusion zone is given by

$$V^r = V^r_{upper} + V^r_{lower} - \text{die cavity} \tag{3}$$

$$V^r_{upper} = (V_f - V_t)\left[W_r + \frac{R_s}{24} + \lambda\delta^2\right] h^u_r t \tag{4}$$

$$V^r_{lower} = (V_f - V_t)\left[\frac{2}{3}\left(W_r + \frac{R_s}{4}\right) + \lambda\delta^2\right] h^l_r t \tag{5}$$

Volume of the material moving through the Advancing side of extrusion zone is obtained as

$$V^a = (V_f + V_t)\left[\frac{2}{3}W_a + \lambda\delta^2\right] ht \tag{6}$$

Assuming the material moved down one tread pitch (1/λ) per revolution, total downward motion is obtained as

$$\Delta Z = \omega t / \lambda \tag{7}$$

Total volume per unit time of the shoulder-processed material is given by

$$V_s = t\omega(R_s - R_p) * h_s / \lambda \tag{8}$$

It is also assumed that the shoulder material fills the volume vacated by the downward motion. The plasticized metal is not allowed to expand freely due to the containment of its solid surrounding and the axial force from the tool. This result in the expulsion of metal at the top surface and the rotation of the tool transport this expulsed metal and deposited them in the retreating side. In this work this volume is assumed as 2~4% Vs depending on the rotation speed. Equating the flow for mass balance will result the equation as

$$V_{DC} = V^e + 0.98V_s \tag{9}$$

By considering quadratic terms of general surface equation, we arrive at the nine-term bi-quadratic function:

$$h_i = a_{00} + a_{10}x + a_{01}y + a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{21}x^2y + a_{12}xy^2 + a_{22}x^2y^2 \tag{10}$$

Occasionally, the x^2y^2 term is omitted,
So the equations for the height of shoulder vortex and extrusion zone from the above surface plots shown in Fig. 5 are

$$h_S = -0.0000237333 \times V_t^2 + 0.000581667 \times V_f^2 + 0.0294817 \times V_t - 0.0774083 \times V_f + 0.0000265 \times V_t \times V_f - 5.65719 \tag{11}$$

$$h_E = -0.000011 \times V_t^2 - 0.00194 \times V_f^2 + 0.02542 \times V_t + 0.31725 \times V_f - 0.000177 \times V_t \times V_f - 9.7983 \tag{12}$$

$$h_V = 0.0000264667 \times V_t^2 + 0.00741667 \times V_f^2 - 0.0382417 \times V_t - 0.106575 \times V_f + 0.0000485 \times V_t \times V_f + 16.9788 \tag{13}$$

$$W_E = 6.66667 \times 10^{-6} \times V_t^2 + 0.000616667 \times V_f^2 - 0.0154333 \times V_t - 0.150667 \times V_f + 0.00009 \times V_t \times V_f + 24.6706 \tag{14}$$

Based on the equation of the analytical model and bi-quadratic function of height of shoulder vortex extrusion zone and width of the stir zone an excel work sheet as shown in the Fig. 6 has been created to calculate the dimension of the stir zone based on the welding parameters.

Thus 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

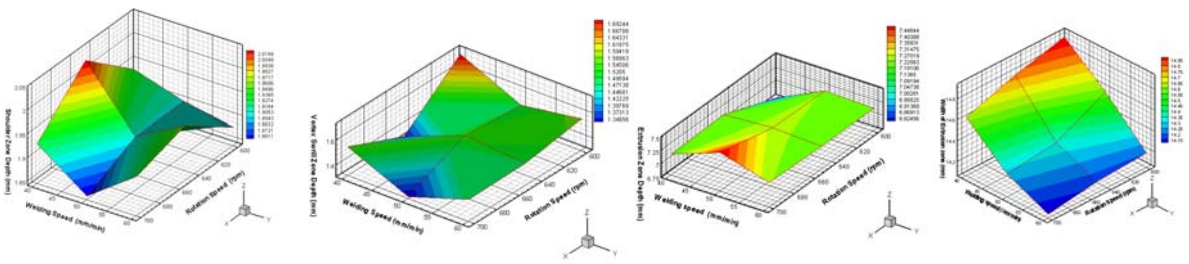

Fig. 5 Shoulder, Extrusion, Vortex zone height and Width of extrusion for various rotations and translational speed of the tool

Variables	Values	units	Calculation Details
Rotational velocity= w	850	rpm	
Height of the pin= h	9	mm	
Top Radius of pin= Rp1	5.78	mm	
Bottom Radius of pin= Rp2	4.15	mm	
time = t	1	sec	
Radius of the shoulder= Rs	16	mm	
Projected area of the tread= del^2	0.04	mm^2	
Pitch of the tread= lamda	1	Nos/mm	
Tangential velocity=Vt	140.675	mm/sec	
Traslational Speed=Vf	45	mm/min	
Height of shoulder Zone=	0.963289675	mm	(-5.65719+ 0.0294817*w- 0.000023733*w*w- 0.0774083*Vf+ 0.0000265*w*Vf+ 0.000581667*Vf*Vf)
Height of Vortex Zone=	2.156671425	mm	(16.9788-0.0382417*w+ 0.0000264667*w*w - 0.106575*Vf + 0.0000485*w*Vf+ 0.000741667*Vf*Vf)
Height of Extrusion zone=	7.43916	mm	(-9.79784+ 0.02542*w -0.000011*w*w + 0.31725*Vf- 0.000177*w*Vf- 0.00194*Vf*Vf)
Total width of extrusion Zone =	14.28014918	mm	(24.6706 - 0.0154333*w + 6.6666*0.000001*w*w - 0.150667*Vf+ 0.00009*w*Vf + 0.000616667*Vf*Vf)
Volume of the Die cavity=V_{DC}	670.275	mm^3	
Volume of material moving through			
upper retreating extrusion zone V^E_{upper} =	3843.567643	mm^3	495.355 Wr + 350.0509
Lower retreating extrusion zone V^E_{lower} =	3649.957997	mm^3	330.237 Wr + 1320.947
~Total retreating extrusion zone side=	7493.52564	mm^3	825.592 Wr + 1670.998
~Total Advancing extrusion zone side=	15720.74688	mm^3	734.865 Wr + 10538.07
~Total extrusion zone side V_E=	22543.99752	mm^3	1560.46 Wr + 11538.8
~Total Shoulder zone V_S=	139.4682901	mm^3	V_{DC} = V_E + 0.98* V_S Gives ---->> Wr= 7.05255
Width of the Retreating side =	7.052550717	mm	
Width of the Advancing side =	7.227598458	mm	

Fig. 6 Excel calculation sheet for determination of the dimensions of the stir zone based on the Friction stir welding parameters

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 this the finite element heat transfer analysis has been carried out.

FE Heat Transfer Analysis

To determine the thermal histories of the Friction Stir welding process the finite element heat transfer analysis has been carried out (Comini et al). The three dimensional FE model employed in this work is shown in the Fig. 4. 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 material used for the modeling was Al 6061 and the temperature dependent physical properties applied for the FE heat transfer analysis.

Results and Discussion

Results of FE based Heat transfer analysis. The three dimensional temperature distribution contours obtained from the FE heat transfer analysis are shown in Fig.7a and 7b. In order to have a clear inside view of the 3D model, slice section along the length width and thickness has been plotted.

Comparison of Numerical and Experimental Results

In order to compare these results with the experimentally measured values, 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 is shown in the Fig. 6. and the corresponding numerically obtained value for time t =2.20 sec is shown in the Fig. 7 and from the graph it can be seen that both the values are comparable. The estimated maximum temperatures are about 467°C in the stir zone and 306°C in the HAZ. The numerically simulated temperature value far from the weld zone has deviation from the experimental results, as the thermal diffusion term is not considered in the numerical model.

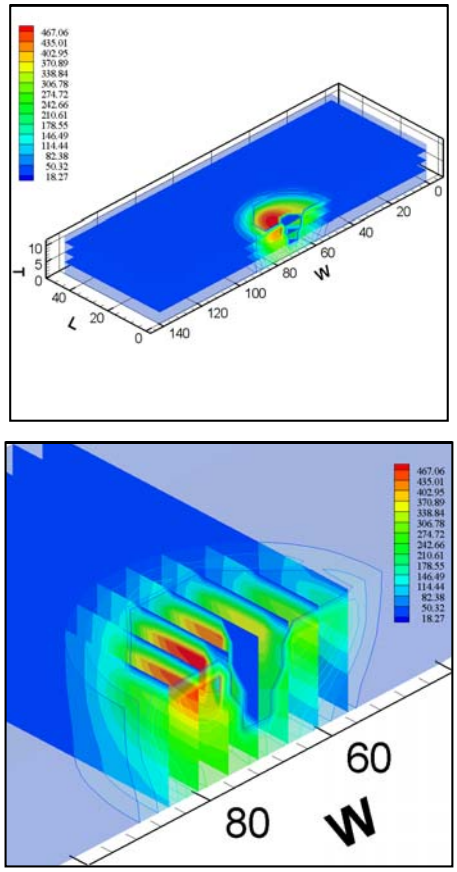

Fig. 7 Temperature distribution contour on the slice (a) along the thickness direction (3mm, 6mm and 9mm from the top) (b) along the width direction (at 0mm, 5mm, 10mm and 15mm from the tool axis along advancing and retreating side)

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 model can be used to accurately model the heat distribution along the uniform processing zone of FSW between the plunging and releasing portions.
2. The three-dimensional asymmetric heat distribution about the tool has been accurately modeled and experimentally validated for Al 6061-T6 12mm thick plate FS welding.
3. The asymmetry in the heat distribution is due to the asymmetry in the plasticized material volume along the advancing and retreating side of the stir zone.

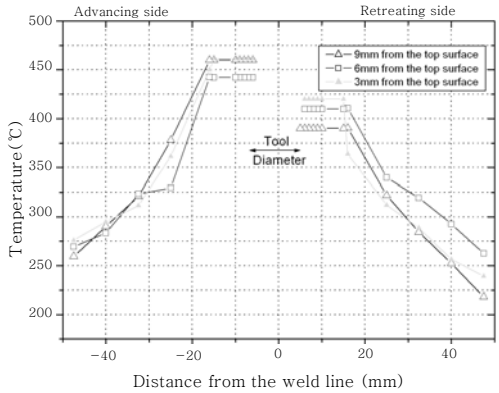

Fig. 8 Temperature distribution at various depths for FSW of 50-travel speed and 600-rotation speed measured using thermocouple

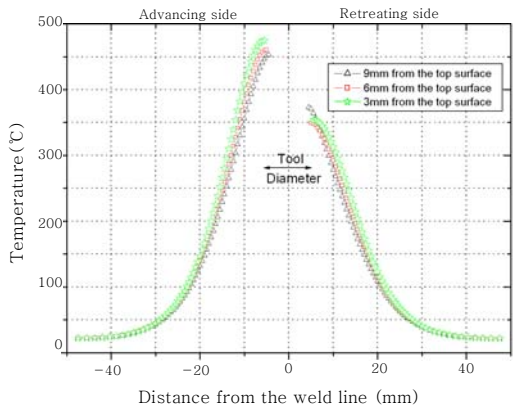

Fig. 9 Temperature distribution at various depths for FSW of 50 travel speed and 600 rotation speed obtained using the analytical model and non linear heat transfer analysis. (at time, t=2.20sec)

Nomenclature

λ : Threads per inch
δ^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
ΔZ : Distance material moves down per revolution
q_{Sa}, q_{Sr} : Rate of heat generated
F_S : Shear plane component of resultant force
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 ω

v_s : Velocity of material in shoulder zone
ω : 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

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