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

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

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

$$V^e = V^a + V^r$$  \hspace{1cm} (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

$$V^r = V^r_{upper} + V^r_{lower} - \text{die cavity}$$  \hspace{1cm} (3)

$$V^r_{upper} = (V_f - V_i) \left[ W_f + \frac{R_s}{24} + \lambda \delta^2 \right] h_i t.$$  \hspace{1cm} (4)

$$V^r_{lower} = (V_f - V_i) \left[ \frac{2}{3} \left( W_f + \frac{R_s}{4} + \lambda \delta^2 \right) \right] h_i t.$$  \hspace{1cm} (5)
Volume of the material moving through the Advancing side of extrusion zone is obtained as

$$V^* = (V_t + V_r) \left[ \frac{2}{3} W_s + \lambda \delta^2 \right] ht$$

(6)

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

$$\Delta Z = \omega t / \lambda$$

(7)

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

$$V_s = t\omega (R_s - R_p) * h_s / \lambda$$

(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 expelled 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

$$V_{DC} = V^* + 0.98 V_s$$

(9)

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

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

(10)

Occasionally, the $x^2 y^2$ 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

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

(11)

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

(12)

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

(13)

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

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

<table>
<thead>
<tr>
<th>Variables</th>
<th>Values</th>
<th>units</th>
<th>Calculation Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational velocity ( \omega )</td>
<td>615</td>
<td>rpm</td>
<td></td>
</tr>
<tr>
<td>Height of the pin ( h )</td>
<td>9</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Tool radius of pin ( r_p )</td>
<td>3.75</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Bottom radius of pin ( r_b )</td>
<td>4.7</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>( z = 1 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radius of the shoulder ( R_s )</td>
<td>14</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Projected area of the tool ( A )</td>
<td>0.34</td>
<td>mm²</td>
<td></td>
</tr>
<tr>
<td>Pitch of the tool ( p )</td>
<td>11</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Tangential velocity ( V_t )</td>
<td>145.47</td>
<td>mm/sec</td>
<td></td>
</tr>
<tr>
<td>Translational Spindle ( V_F )</td>
<td>45</td>
<td>mm/min</td>
<td></td>
</tr>
<tr>
<td>Height of shoulder Zone ( \theta_1 )</td>
<td>0.9532883757</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Height of Vapor Zone ( \theta_2 )</td>
<td>2.1566746529</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Height of Extrusion zone ( \theta_3 )</td>
<td>7.4396</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Total width of extrusion Zone ( \lambda )</td>
<td>14280149.051</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Volume of the Core ( V_{core} )</td>
<td>478.229</td>
<td>mm³</td>
<td></td>
</tr>
<tr>
<td>Volume of material moving through upper extrusion zone ( V_{up} )</td>
<td>26543.3576385</td>
<td>mm³</td>
<td></td>
</tr>
<tr>
<td>lower extrusion zone ( V_{low} )</td>
<td>3646.317049</td>
<td>mm³</td>
<td></td>
</tr>
<tr>
<td>Total extrusion zone ( V_{ex} )</td>
<td>30199.7</td>
<td>mm³</td>
<td></td>
</tr>
<tr>
<td>Total Advancing extrusion zone ( V_{Adv} )</td>
<td>15720.786103</td>
<td>mm³</td>
<td></td>
</tr>
<tr>
<td>Total extrusion zone ( V_{Adv} )</td>
<td>22543.397582</td>
<td>mm³</td>
<td></td>
</tr>
<tr>
<td>-Total shoulder zone ( V_{sh} )</td>
<td>139682815</td>
<td>mm³</td>
<td></td>
</tr>
<tr>
<td>Width of the Retracting side ( \delta )</td>
<td>7.0525057</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Width of the advancing side ( \delta )</td>
<td>7.097538488</td>
<td>mm</td>
<td></td>
</tr>
</tbody>
</table>

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

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.
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.

Nomenclature

$\lambda$ : Threads per inch
$\delta^2$ : Projected thread area
$W_a$ : Width of advancing extrusion zone
$W_r$ : Width of retreating extrusion zone
$W_s$ : Average width of shoulder zone
$\Delta Z$ : 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 $R_p \omega$
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\( v_s \) : Velocity of material in shoulder zone
\( \omega \) : 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

References