NUMERICAL MODELING OF THERMAL FIELD DURING FRICTION STIR WELDING USING NON-CIRCULAR PIN

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ABSTRACT

Friction stir welding (FSW) has significant advantages over fusion welding as the welding is done in solid state. Especially this pure solid state joining results reduced distortion and improved mechanical properties on the usage of non-circular tool pins. In this paper, a simplified model is developed in MATLAB based on the moving coordinate system to analyse the thermal field developed by the various polygonal shaped tool pin profiles during the process. Peak temperature generated in the welding stage is derived and compared on the usage of different tool pin geometries and their corresponding temperature distribution along the base metal is numerically modelled using Rosenthal equation. This model also describes the heat generation due to the friction between the tool shoulder and the workpiece by considering the variation in the geometrical shape of the shoulder/matrix interface corresponding to the selected tool pin profiles. The aim of the model is to provide a predictive capability for FSW temperature fields directly from the material properties and tool design.

Key words: Friction stir welding, thermal model, numerical modeling, non-circular tool pin.

1. INTRODUCTION

Friction stir welding (FSW) is a novel and promising welding technique that has not yet been fully investigated, described or utilised though it is invented three decades before. It is a solid state joining process of two metals or alloys using relatively simple equipment. This welding technique does not require consumables or shielding gas to weld aluminium alloys in order to prevent molten metal oxidation, as the joining process is carried out in solid state. Welding is performed with a specialized, usually cylindrical welding tool which is mounted in the spindle of a machine that can rotate the tool around its axis. This rotating cylindrical shouldered tool plunges into the butted plates and locally plasticizes the joint region during its movement along the joint line that causes a join between the work pieces [Fig. 1] [1]. A complex physical process in and around the parts that are joined produces a monolithic structure in the joint. During FSW, the friction between the weld material and the welding tool generates heat which causes the weld material to soften in a temperature lesser than the melting point [Fig. 2] [1]. Joining is produced by the welding tool which plasticises, deforms and stirs the metal throughout the weld line during its rotary and sliding movement over the base metals along the joining line. As joining is done in solid state, metal joint has less residual stress and distortion comparing to fusion welding.
The post weld properties on the joint depend on the thermal cycles developed during the process. The analysis of thermal field can predict the weld quality which reveals the importance of thermal modeling to optimise the weld input variables in the view of enriching the post weld properties of the joint. Shi et al. [2] studied temperature results through finite element analysis conducted using ABAQUS. Their thermo-mechanical analysis was verified by experiments, which proved that the heat source model developed by them is sufficiently accurate. Two dimensional finite element model developed by Lockwood and Reynolds [3] for friction stir welding in aluminium alloy 2024-T351. The results are validated by experimental data and have been corroborated by a three-dimensional FE model. Song et al. [4] simplified heat generation from the tool pin as a moving heat source. However, these assumptions are not helpful in tool pin and workpiece coupled heat transfer modelling. An analytical model for various tool contact conditions, namely sliding, sticking and partially sticking condition was proposed by Schmidt et al [5] for heat generation. The experimental data on heat generation rate are similar to the sticking condition at tool/matrix interface of AL2024-T3 alloy. Ullessy [6] evaluated the effect of tool speed on temperature field by developing a three- dimensional viscoelastic model using computational fluid dynamics. A three dimensional finite element model is developed using ANSYS package by Rajamanickam et al. [7] to study the thermal history in the butt welding of 6061 aluminium alloy. Temperature distributions of the weld at various welding speeds are obtained and verified with experimental data. Zhan et al. [8] estimated the amount of energy transmitted to the workpiece and the amount of energy converted as frictional heat by using coupled thermo-mechanical finite element model. A better simulation was obtained by Li et al. [9] using ABAQUS software for the fully sticking condition of tool-workpiece interface. Sanjeev et al. [10] analysed the influence of friction coefficient on the simulation output using ABAQUS and found coefficient of friction is equal to 1.0 during sticking condition. Most of the numerical thermal models are developed assuming tool pin shape as circular. There are limited steadies are made [11] with non-circular tool pins. Complicated geometrical boundary of these tool pin profiles with respect to the axis of rotation makes it difficult to analyse. The objective of this paper is to study the temperature history on the heat affected zone and weldment on the usage of different polygonal pin profiles. Hence understanding the distribution of heat and obtaining the temperature contours will assist in understanding the post weld properties of the friction stir weld joints.

2. ANALYTICAL MODELLING

During welding stage, generated heat along the tool/matrix interface increases the temperature of the material in contact with the tool towards its melting point. When the temperature reaches closer to the melting point the material tends to become liquid stage and coefficient of friction drops tremendously and tool looses its
grip. This drop in friction in the contact surface makes the tool to slide without developing further frictional heat which in turn reduces the temperature. This cyclic process continues and a quasi-static stage [4] is attained and the peak temperature reaches its steady state.

2.1. Governing equations

Steady state thermal field during the process can be estimated through the general non-linear three dimensional heat transfer equation. This can be expressed as

\[ \frac{\partial}{\partial x} \left( K_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial T}{\partial z} \right) + Q_{\text{Total}} = \rho C_p \left( \frac{\partial T}{\partial t} - U_w \frac{\partial T}{\partial \xi} \right) \]  

(1)

where \( K \) represents the thermal conductivity of the material, \( \rho \) is density, \( C_p \) is specific heat capacity, \( T \) is temperature and \( t \) represents time.

If the tool moves along the joint with an velocity of \( U_w \) and if the movement of tool is assumed along x axis, then the moving coordinates system (\( \xi, y, z \)) can be written as

\[ \xi = x - U_w t \]  

(2)

Which can be explained as \( \xi \) is the distance of the heat source at any instance of time (\( t \)). Applying this in equation (1), it can be modified as

\[ \frac{\partial}{\partial \xi} \left( K_\xi \frac{\partial T}{\partial \xi} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial T}{\partial z} \right) + Q_{\text{Total}} = -\rho C_p U_w \frac{\partial T}{\partial \xi} \]  

(3)

In this equation change in temperature with respect to time \( \frac{\partial T}{\partial t} \) becomes zero as the current heat transfer analysis is done in welding stage where thermal field attains quasi steady state.

Here, total heat generated can be calculated by the empirical model developed by Gadakh et al. [11], in which total heat generated by the different pin profiles are calculated by

\[ Q_{\text{Total}} = \frac{2}{3} \pi \tau_{\text{contact}} \omega \left( R_3^3 \text{shoulder} + X R_2^2 \text{pin} \right) \]  

(4)

where multiplication factor \( X \) depends on the number of sides \( n \) in the tool pin. \( X \) = 0.72, 0.95, 1.19, 1.43 when the number of sides \( n = 3, 4, 5, 6 \) respectively.

2.2. Analytical solution

Three assumptions made in order to attain a closed form of solution for the proposed model are (i) input source is a point heat source; (ii) variation in the thermal properties of the material with respect of the temperature is negligible; and (iii) heat transfer is under quasi steady state. Based on these assumptions, equation (3) is solved to obtain temperature at any point [12] as

\[ T = \left( \frac{Q_{\text{Total}}}{2\pi K_t} \right) e^{-\frac{\left( -\frac{\xi^2}{2\alpha} \right)}{2\alpha}} K_0 \left( \frac{U_w r}{2\alpha} \right) + T_0 \]  

(5)

Here, \( r = \sqrt{\xi^2 + y^2 + z^2} \), \( \alpha \) is thermal diffusivity, \( K_0 \) is modified Bessel function, \( t \) is thickness of the plate in \( z \) direction, \( T_0 \) is initial temperature of the plate to be joint.

3. NUMERICAL MODELING

Three dimensional numerical thermal modeling are carried out in MATLAB, adopting moving coordinate point heat source input, using Rosenthal equation during welding stage. Thermal field developed during the process is analysed in Al2024 plates. The properties of the material considered for the analysis is given in Table.1. In order to analyse the variation in thermal field on the usage of different non-circular tool pin geometries \( n = 3, 4, 5 \& 6 \), heat input is varied according to the pin shape used in the model which is calculated analytically using equation (4). Heat input variation with respect to the number of sides in the tool pin.
is given in Table 2. Effective heat supply ($Q_{eff}$) during welding depends on the welding speed and the maximum temperature raise ($T_{max}$) in the welding period depends on $Q_{eff}$. Input heat supply for the current model is evaluated through the ratio between obtained total heat generated (Eqn.4) and the welding speed. For the validation of the proposed model, the effective heat supply is calculated for the experimental conditions adopted by Padmanaban et al.[13] and Obtained $T_{max}$ is compared (Table 2) with experimental result.

Table 1. Input properties/parameters

<table>
<thead>
<tr>
<th>Property/parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder radius (mm)</td>
<td>9</td>
</tr>
<tr>
<td>Circumscribed pin radius (mm)</td>
<td>3</td>
</tr>
<tr>
<td>Height of the pin (mm)</td>
<td>5.4</td>
</tr>
<tr>
<td>Workpiece thickness (mm)</td>
<td>6</td>
</tr>
<tr>
<td>Specific heat capacity of workpiece (J kg$^{-1}$ K$^{-1}$)</td>
<td>875</td>
</tr>
<tr>
<td>Thermal conductivity of workpiece (W m$^{-1}$ K$^{-1}$)</td>
<td>121</td>
</tr>
<tr>
<td>Applied force (kN)</td>
<td>9</td>
</tr>
<tr>
<td>Tool rotation speed (rpm)</td>
<td>800</td>
</tr>
<tr>
<td>Initial temperature of workpiece (K)</td>
<td>300</td>
</tr>
<tr>
<td>Weld velocity (cm/min)</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2. Heat input for different pin profile

<table>
<thead>
<tr>
<th>Pin profile</th>
<th>Number of sides in the tool pin (n)</th>
<th>Effective heat supply ($\frac{Q_{rot}}{Weld velocity}$) (J/mm)</th>
<th>Peak temperature obtained (C)</th>
<th>Peak temperature (Experimental) (C) [13]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangular</td>
<td>3</td>
<td>744.67</td>
<td>347.48</td>
<td>341</td>
</tr>
<tr>
<td>Square</td>
<td>4</td>
<td>756.14</td>
<td>352.42</td>
<td>346</td>
</tr>
<tr>
<td>Pentagon</td>
<td>5</td>
<td>768.11</td>
<td>357.57</td>
<td>350</td>
</tr>
<tr>
<td>Hexagon</td>
<td>6</td>
<td>780.08</td>
<td>362.72</td>
<td>364</td>
</tr>
</tbody>
</table>

Three dimensional model shown in Figs.3(a) to (d) explain the thermal field produced along the tool path developed by the different tool pin geometries viz triangular, square, pentagonal and hexagonal pins respectively in the workpiece. Variation in the attained peak temperature clearly explains the influence of increase in the number of sides in the tool pin. Maximum peak temperature of 362.75°C is observed for hexagonal tool pin. When the number of sides in the tool pin increases, contact surface area along the tool/matrix interface also increases. As the frictional heat generation depends on the contact surface area, it results comparatively high intensity of heat input for hexagonal shaped pin profile which results higher process temperature on the given welding speed.
3.1. Heat affected zone

High intensity of heat generation not only increases the process temperature but also it increases heat affected zone in the parental metal. From Fig.4, it can be understood that the width of the heat affected zone increases nearly 8 mm on the usage of hexagonal tool pin comparing with triangular pin shape. Heat affected zone is the area where bigger grain size is observed in the microstructure analysis [14] and it is the area in which failure happens in FSW joints. So from the analysis it can be concluded that the tool with triangular pin results in lesser heat affected zone comparing with other pin profiles which in turn provides superior weld quality. Microstructure and mechanical property analysis done by Bayazid et al. [15] also supports the predicted model shown in Fig.4. as they found reduce in the number of sides in the tool pin increases weld quality.
4. EFFECTS OF TOOL DESIGN

Apart from the geometrical shape, geometrical dimension of the tool is also a major factor to be considered in the analysis of thermal field. Being a major contributor of the total heat supply, shoulder diameter design is the key area to be considered on optimising the generated peak temperature during the process. Required heat input can be balanced by adjusting the ratio between the shoulder diameter ($D$) and the tool pin circumferential diameter ($d$) irrespective of tool pin shape. Post weld property analysis done by Padmanaban et al. [13] clarifies that $D/d$ ratio has a definite influence in the weld quality. In order to analyse the change in temperature field on the change in $D/d$ ratio in various pin profiles, peak temperature developed is calculated using the equation derived by Hamilton et al [16]. It can be evaluated by

$$T_{\text{max}} = 1.56 \times 10^{-4} \times Q_{\text{eff}} + 0.54$$  \hspace{1cm} (6)

Effective heat supply ($Q_{\text{eff}}$) during welding depends on the welding speed and the maximum temperature raise ($T_{\text{max}}$) in the welding period depends on $Q_{\text{eff}}$ and solidus temperature ($T_s$) of the material. From the obtained results shown in Figs. 5 and 6, it is evident that irrespective of tool pin shape, required thermal field can be obtained through the exact selection of $D/d$ ratio. For example, a maximum of 735.8 K can be achieved in triangular shape when $D/d$ is equal to 4, mean while a minimum of 531.9 K can be achieved in the hexagonal tool pin on the selection of $D/d$ ratio as 2.
5. CONCLUSIONS

A three dimensional numerical thermal model using Rosenthal equation has been developed in MATLAB. Obtained variations in heat distribution on the usage of different pin geometries are validated with experimental data. This model accurately predicts the effects of increase in the number of sides on the peak temperature which eliminates the difficulty of measuring temperature in the stir zone during welding. Predicted temperatures at various points are used to forecast the possible size of heat affected zone and it is observed that the usage of hexagonal pin increases the heat affected zone. As the failure happens in heat affected zone in FSW, it can be concluded that usage of triangular pin results in better weld quality as it exhibits comparatively smaller heat affected zone. Further, effects of increasing the ratio between shoulder and pin diameter \((D/d\) ratio) on the heat input and peak temperature are also examined for various tool pin profile through which it is understood that controlling of heat affected zone can be done by adjusting the tool dimensions.

REFERENCES


