Numerical modeling of thermal field during friction stir welding using tool with polygonal pin profile

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Abstract. Friction stir welding produces better joint strength comparing with other conventional fusion welding techniques as the complete metal joining operation is executed in solid state itself. Even though the quality of weld is comparatively good, this joining technique has its own disadvantages. Improper material flow along the weld line may result in weld defects. Usage of polygonal pin geometry in tool pin rather than using conventional cylindrical pin geometry enhances flow of plasticized metal under the tool shoulder in the stir zone. Major problem associated with polygonal shaped tool pin is poor tool life. Yield strength of material under the tool shoulder creates opposing force for the movement of tool pin, which is submerged inside the workpiece for the entire joining process. Uneven stress distribution along the outer surface of the polygonal tool pin shape leads to premature tool failure. As the strength of material is a temperature dependent property, the heat input during the process has to be optimised with respect to the geometrical shape of the tool pin to improve tool life without compromising the weld quality a lot. In this paper, the variation in thermal field based on the geometrical shape of the tool pin was analysed using MATLAB based on the moving coordinate system. Rosenthal equation was used to estimate variation the peak temperature and temperature distribution with respect to pin shape in the view of optimising thermal environment towards better weld quality.

Keywords: Friction stir welding, thermal model, numerical modeling, polygonal tool pin.

1. Introduction

Friction stir welding (FSW) is predominately used to join aluminium sheets, as it is impossible to weld using conventional other fusion welding techniques [1]. Plates are joined using simple equipment
without melting the base metal material in this joining technique. The major advantage of this relatively novel joining process is, it does not require consumables or inert gas shielding to weld aluminium alloys in order to prevent molten metal oxidation. This welding technique is performed by the rotating tool, which has cylindrical shaped tool pin and shoulder. This rotating tool slides over the clamped metal pieces along the weld line. The relative velocity between the contact surfaces of the tool and the base metal produces heat due to friction along the tool/matrix contact interface [2]. When this frictional heat is sufficient to plasticise the base metal under the shoulder of the tool, the toque developed by the rotating tool creates plastic deformation of material along the weld line. The extruded material from the advancing side is forged in the retreating side during the forward motion of the friction stir weld tool as shown in Fig.1. This process continues during welding stage and joint is created without melting the base metal along the weld line.

![Figure 1. Solid state material joining in FSW [3]](image)

The post weld properties on the joint depend on the thermal field grown during the joining 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. Li et al. [4] analysed temperature gradient with respect to the distance from heat supply boundary using ABAQUS. Their thermal field predictions were validated with experimental results and the heat source model developed by them is sufficiently accurate. Two-dimensional finite element model developed by Abubakr et al. [5] during the joining of aluminium alloy 2024-T351 plates. The fatigue crack growth in heat-affected zone was analysed using finite element method correlating the process parameters and post weld properties. Song et al. [6] simplified heat generation model by converting the heat source surface as point heat source. However, these assumptions cannot be used to analyse the heat supply variations along various contact surfaces like tool shoulder/matrix and tool pin/matrix interfaces. An analytical model for various tool contact conditions, namely sliding, sticking and partially sticking condition was proposed by stephen et al [7] for heat generation using tool with non-circular tool pin. The experimental data on heat generation rate are verified through temperature rise during friction stir welding of AA 2024-T3 alloy. Subarata et al. [8] evaluated the influence of weld speed on temperature field by developing a three-dimensional model using computational fluid dynamics and partition of heat between tool and matrix were estimated in their analysis. ANSYS based finite element model was generated by Rajamanickam et al. [9] to analyse the temperature rise in the butt welding of AA6061. Temperature distributions of the weld at different weld velocities were obtained and verified with experimental data. Zhan et al. [10] used coupled thermo-mechanical analysis in the view of estimating the ratio between the total heat generated in the contact surface and the heat effectively supplied into the workpiece using finite element model. Apart from this, few researchers [11] analysed the effect of weld quality and thermal history variations on the usage of non-circular pin geometry. Sanjeev et al. [12]
analysed the effect of tool pin geometry on the joint quality and found that non-circular pins were delivering better weld quality. Most of the numerical thermal models are developed assuming tool pin shape as circular. There are limited studies made 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 core aim of this paper is to understand the variation on thermal field developed on the heat affected zone as well as stir zone on the usage of different polygonal pin profiles in friction stir welding. The obtained temperature contours were used to understand the property eradication in the stir zone as well as heat affected zone through which a convenient thermal condition was defined to obtain highly efficient weld joint.

2. Analytical Modeling

During welding stage, generated heat along the contact interface of tool and matrix increases the temperature of the base metal in contact with the tool towards its melting point. When the increase in temperature nearer to the melting point, the material tends to become liquid state 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 [14,15] 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

$$\frac{\partial}{\partial \xi} \left( K_x \frac{\partial T}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left( K_y \frac{\partial T}{\partial \eta} \right) + \frac{\partial}{\partial \zeta} \left( K_z \frac{\partial T}{\partial \zeta} \right) + Q_{\text{Total}} = \rho C_p \left( \frac{\partial T}{\partial \tau} - U_w \frac{\partial T}{\partial \xi} \right)$$  

(1)

where $K$ represents the thermal conductivity of the material, $\rho$ is density, $C_p$ is specific heat capacity, $T$ is temperature and $\tau$ represents time. If the tool moves along the joint with a velocity of $U_w$ and if the movement of tool is assumed along $\xi$ axis, then the moving coordinates system ($\xi$, $\eta$, $\zeta$) can be written as

$$\xi = \eta - U_w \tau$$  

(2)

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

$$\frac{\partial}{\partial \xi} \left( K_x \frac{\partial T}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left( K_y \frac{\partial T}{\partial \eta} \right) + \frac{\partial}{\partial \zeta} \left( K_z \frac{\partial T}{\partial \zeta} \right) + Q_{\text{Total}} = -\rho C_p U_w \frac{\partial T}{\partial \xi}$$  

(3)

In this equation change in temperature with respect to time ($\frac{\partial T}{\partial \tau}$) 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. [15],

$$Q_{\text{Total}} = \frac{2}{3} \pi \tau \eta \rho \left( R_{\text{shoulder}}^3 X \right) + \pi R_{\text{pin}}^3 H_{\text{pin}}$$  

(4)

Where multiplication factor $X$ depends on the number of flat faces $(n)$ 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 [16] as

$$T = \frac{Q_{\text{Total}}}{2\pi Kt} e^{-\frac{U_w \xi}{2\alpha t}} K_o \left( \frac{U_w}{2\alpha t} \right) + T_0$$  

(5)

Here, $\tau = \sqrt{\xi^2 + \eta^2 + \zeta^2}$, $\alpha$ is thermal diffusivity, $K_o$ is modified Bessel function, $t$ is thickness of the plate in $\zeta$ 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 AA2024-T3 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 polygonal shaped 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 \( Q_{\text{eff}} \) during welding depends on the welding speed and the maximum temperature raise \( T_{\text{max}} \) in the welding period depends on \( Q_{\text{eff}} \). 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 Padmananban et al. [17] and Obtained \( T_{\text{max}} \) is compared (Table.2) with experimental result.

Table 1. Parameters and properties used in the model.

| Property/parameter | Value |
|--------------------|-------|
| \( R_{\text{Shoulder}} \) (mm) | 9 |
| \( R_{\text{Pin}} \) (mm) | 3 |
| \( H_{\text{Pin}} \) (mm) | 5.6 |
| \( t \) (mm) | 6 |
| \( C_p \) of base metal (J kg\(^{-1}\) K\(^{-1}\)) | 880 |
| \( K \) of base metal (W m\(^{-1}\) K\(^{-1}\)) | 124 |
| Vertical force (kN) | 9 |
| Rotational speed of the tool (rpm) | 800 |
| \( T_0 \) of base metal (℃) | 27 |
| \( U_w \) (mm/min) | 100 |

Table 2. Heat input for different pin profile

| Pin profile | \( n \) | \( \frac{Q_{\text{total}}}{\text{Weld velocity}} \) (J/mm) | Peak temperature obtained (℃) | Peak temperature (Experimental) (℃) [13] |
|-------------|--------|--------------------------------|-------------------------------|---------------------------------|
| Triangular  | 3      | 744.67                        | 347.48                        | 341                             |
| Square      | 4      | 756.14                        | 352.42                        | 346                             |
| Pentagon    | 5      | 768.11                        | 357.57                        | 350                             |
| Hexagon     | 6      | 780.08                        | 362.72                        | 364                             |

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 variation in the number of flat faces in the tool pin. Maximum peak temperature of 362.75℃ is observed for hexagonal tool pin. The increase in number of flat faces in tool pin increases the contact surface area along the tool/matrix interface as well. 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 total heat supply not only increases the process temperature but also it increases heat affected zone in the base 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 [18] and it is the area in which failure happens in FSW joints. So from the analysis it can be understood 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. [19] also supports the predicted model shown in Fig.4 as they identified reduction in the flat faces along the tool pin vertical surface increases weld quality.

![Figure 3](image)

**Figure 3.** Three-dimensional heat distribution analysis in MATLAB for (a) triangular pin, (b) square pin, (c) pentagonal pin, (d) hexagonal pin

### 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. [17] 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 [20]. It can be evaluated by

\[ \frac{\text{T}_{\text{max}}}{\text{T}_s} = 1.56 \times 10^{-4} \times \text{Q}_{\text{eff}} + 0.54 \]  

(6)

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} and solidus temperature (T_s) of the material [21]. 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.

Figure 4. Heat affected zone when (a) n=3, (b) n=4, (c) n=5, (d) n=6.

Figure 5. Effective heat input variation

Figure 6. Peak temperature variation
5. Conclusions

A three-dimensional numerical thermal model using moving heat source method had 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 were used to forecast the possible size of heat affected zone and it was concluded that the size of heat affected zone is directly proportional to the number of flat faces in tool pin. As the failure happens in the heat affected zone in FSW, it can be concluded that usage of triangular pin results is 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.

| Symbols | Descriptions |
|---------|--------------|
| $\tau$  | Time (s)     |
| $U_w$   | Weld velocity (mm/min) |
| $t$     | Plate thickness (mm) |
| $K_o$   | Modified Bessel function |
| $\alpha$ | Thermal diffusivity ($m^2/s$) |
| $R_{\text{Shoulder}}$ | Radius of the tool shoulder (mm) |
| $R_{\text{pin}}$ | Circumferential radius of tool pin (mm) |
| $H_{\text{pin}}$ | Tool pin height (mm) |
| $r$     | Distance from axis of rotation (mm) |
| $n$     | Number of flat faces in tool pin |

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