A Review on Heat Generation and Temperature Distribution Models in Friction stir Welding (FSW)

Bharat Singh¹,a, Shailesh Sharma¹, Veneet Kumar¹, Kunal Maheshwari¹, Piyush Singhal¹

¹Department of Mechanical Engineering, Institute of Engineering and Technology, GLA University Mathura UP India 281406

Corresponding author’s e-mail address: singhbharat09@gmail.com

Abstract. Nowadays the higher fuel efficiency is a major concern in every developing field of technology and it is also a cause for the development of lightweight materials. There are many applications in which it is required to join two dissimilar lightweight materials. Friction stir welding (FSW) is the most crucial development for such types of applications. This technique helps in overcoming the challenges raised during the joining of two dissimilar materials due to their incompatibility with conventional welding techniques. The lightweight materials developed with the help of friction stir welding (FSW) have applications in various industrial sectors like automotive, electronics, shipbuilding, railways, marine, and many others. It is inevitable in joining the different grades of materials like magnesium alloys, aluminum alloys, and low carbon steels without any weld defect. The thermal properties like heat generation and peak temperature also have a significant effect on the quality and strength of the weld joint. The thermal properties change the microstructure of the weld material and influence the mechanical properties of the welded material. This provides Temperature controlling methods so as to reduce the surface temperature and hence reduce the defects in the welded material. This present review article is based upon the summary of the work carried out by different researchers in the field of thermal modeling of the friction stir welding (FSW).

Keywords: Friction Stir Welding, Heat generation, Thermal Modeling, FSW parameters

Introduction

Friction Stir welding is an autogenous, solid-state welding process that was invented in the 1990s[1]. It is used to join similar as well as dissimilar light weight and high strength materials like Al and Mg alloys [2]. In the current industrial scenario, it is preferred to use light weight and high strength materials in various applications and the metal matrix nano composites are the best example of such type of materials [3]. In Friction Stir welding a non-fusible tool rotating at high speeds is passed through abutted metallic workpieces. The tool has a relatively higher strength than that of the workpiece material. The heat generated by the rotating tool fuses the workpieces below the melting point and joins them unlike of conventional fusion welding [4]. The heat is majorly generated due to the friction arising between the tool and the metallic plates. The movement of the tool probe in the workpiece material leads to the plastic deformation of the material surrounding the tool probe. The heat produced due to the plastic deformation further softens the material and completes the weld [5]. The tool has a probe of diameter lower than that of the tool shoulder. This prevents the material from expelling the metallic workpieces. To increase the amount of heat generated due to friction and the mixing of materials, the tool probe is generally threaded. The high-quality strength of the friction-stir
welded materials may be accredited to the plastic deformation and below melting point solidification [6]. The thermal modeling and heat generation analysis of friction stir welding and in conventional welding is extremely important as it decides the temperature field, weld quality and the melting efficiency [7]. The welding quality is also influenced by the tool and weld parameters [8] and there are various methods to optimize these parameters like SRM, Taguchi method and many others [9]. The mathematical modeling of the temperature distribution and heat generation generally take the effects of the different weld and tool parameters into consideration [10]. The modeling reduces the experimental effort required for the development of the design and parameters of FSW and helps in the prediction of the welding parameters, experiment, and tool design by analyzing the heat generation and temperature distribution [6]. The influence of tool geometry is very much significant as it influences the flow and heating of the material and the stirring action of the tool. The effects of tool parameters and their effects on friction stir welding are summarized in Table 1.

| Tool feature          | Intended effect                                                |
|-----------------------|---------------------------------------------------------------|
| Flat probe tip        | Higher penetration ligaments and better TMAZ penetration       |
| Threads on probe      | Compression of the weld zone                                  |
| Flats or other re-entrant features | Thicker weld section, higher heat input                  |
| Flare probe profile   | Wider root profile                                            |
| Frustum probe profile | Thicker weld section and reduced lateral forces               |
| Tapered shoulder      | Variable shoulder penetration and variable shoulder contact width |
| Shoulder scroll       | Containment of softened workpiece material and elimination of tool tilt need |

The tool design has a major role in the modeling of the Heat generation and Temperature analysis. The tool design accounts for the plastic deformation and the adiabatic heat production during the friction stir welding process. The tool shape influences the amount of heat production and temperature change. Biswas et al. [12] studied the effects of tool geometries on temperature distribution in AA1100. The study reported that tools with a concave shoulder lead to lesser temperature rise. It was also reported that the cylindrical tool probe gives rise to larger peak temperatures as compared to conical tool probes of the same diameter. Buffa et al. [13] studied the effect of tool designs on heat production. The study found that the increase in tilt angle gave rise to more heat and a larger temperature rise. The study reported that conical pins produce a helical movement which facilitates the uniform distribution of the material in the weld pool and thus leads to a uniform temperature and heat distribution. Different types of tools are reported in the literature and some of pin profiles are presented in Figure 1.
Figure 1: Types of tool profiles used in the previous studies [5]

The process parameters and their effects on Friction Stir Welding are summarized in Table 2:

| Parameters            | Description/Effects                                                                 |
|-----------------------|-------------------------------------------------------------------------------------|
| Tool design           | Probe length, feature on the probe, shoulder diameter, and scroll or concave shoulder |
| Tool travel speed     | Affects total heat input, Heat input control and the appearance of the weld          |
| Tool rotation rate    | Affects total heat input, Proper mixing of fused materials, heat generation due to friction and oxide layer breaking |
| Material thickness    | Affects temperature gradient and cooling rates                                      |
| Tool tilt             | Typically, in the range of 0 to 3°, Thinning and the appearance of the weld         |
| Cooling rate          | Active or passive cooling                                                            |
| Alloy composition     | Weld parameters which are unique for each alloy                                      |
| Initial material temper| Affects alloy response                                                              |
Surface oxides | Potential for more or less oxide within the weld
---|---
Post weld heat treatment | Depends on alloy composition and pre weld temperature
Joint design | Butt, lap and fillet joints
Test sample size, orientation, and location | Where the sample is sectioned from the weld, especially through the longitudinal vs transverse orientation and the thickness
Heat sink | Thermal conductivity of the material that is in contact with the weld
Plunge force | Proper contact conditions and Frictional heat generation

In the present work an attempt has been made to review the various mathematical models available in the literature to determine heat generated and temperature distribution on the Friction stir welded plate.

2. Mathematical modeling for heat generation and temperature Distribution

In the present section, the study of different models used for heat generation and temperature field calculations are presented and discussed.

2.1. Model Using ‘R’ programming:

Kumar et. al. [15] has developed an equation for the prediction of maximum welding temperature with the help of the R programming language. The author has performed several experiments on AA 6061-T6 Aluminium alloy and recorded the temperature values of the stir zone with the help of a thermal imaging camera. The design of the experiment is based on the full factorial method. In this investigation, the author has considered only two welding parameters- the speed of rotation (RPM) and the speed of welding (mm/min.). In the end, the author has introduced a prediction equation (Eq. 1). A statistical method ANOVA and the scatter diagram was used to check the accuracy of the model. The graph between the predicted peak temperature and the measured peak temperature is presented in Fig. 2.

$$\text{Max. process temperature (oC)} T_{\text{max}} = 281 + 0.03689 \cdot V_{\text{Rotational}} + 0.3266 \cdot V_{\text{Traverse}}$$  \hspace{1cm} (1)
2.2. Analytical Model for Heat generation for Tapered Probe:

Kumar et. al. [16] has presented an analytical model for the heat generation for a tapered probe in friction stir welding. In this work, the presented model is a modified model of previous researchers and the author has validated the results of the model with the data procured from the work of previous researchers and by investigating the results the author has found that there is less heat generation in the tapered cylindrical pin as compared to the straight cylindrical pin. The current modified model is compared with the previous models. In this model, the author has calculated the heat generation at three different surfaces – at the tool side surface, under the tool shoulder surface, and at the tip of the tool probe and developed a mathematical equation for total heat generation. The author has taken several experiments with different Aluminium alloys and different input parameters. Fig. 3 shows the comparison between the proposed modified model and the previous models. Heat energy generated per unit weld length is given in Eq. 2. Based on the Heat energy generated per unit length, peak temperature of over the welded surfaces calculated as per the Eq. 3

\[
\dot{E} = \frac{2}{3} \cdot \frac{\mu}{\nu R_s^2} \cdot (R_s^3 - R_{pt}^2) + \frac{2}{3} \cdot \frac{H_p \cdot \cos \alpha}{\nu R_s} \cdot (2 \cdot R_{pt} - H_p \cdot \tan \alpha)^2 + (R_{pt} - H_p \cdot \tan \alpha)^3
\]  

(2)

Where, \( \dot{E} \) = Heat energy per unit weld length, \( \mu \) = friction coefficient, \( \omega \) = tool angular rotation speed (rad/s), \( \alpha \) = tool pin taper angle (°), \( \nu \) = tool translational speed (m/s), \( \sigma \) = contact pressure (Pa), \( R_{pt} \) = tool probe radius (mm) (taper), \( R_p \) = tool probe radius (mm) (straight), \( R_s \) = tool shoulder radius (mm), \( H_p \) = tool probe height (mm), \( t \) = workpiece thickness(mm), \( h \) = pin length(mm)

\[
Q_{\text{Effect}} = \left( \frac{h}{t} \right) \cdot \dot{E}
\]

Where, \( Q_{\text{Effect}} \) = Effective heat energy

For the validation of the model, the author has used the empirical equation given by Hamilton et. al. [17] is mentioned below.

\[
\frac{T_{\text{max}}}{T_s} = 1.56 \times 10^{-4} \cdot Q_{\text{Effect}} + 0.54
\]  

(4)
The author also investigated the effect of taper angle on the peak temperature for different aluminum alloys and concluded that on increasing the taper angle of the probe the peak temperature decreases as shown in Fig. 4(a-c)

Figure 4: Comparison of Max. temp. and Taper angle for a) AA 6061-T6; b) AA 6061-T65; c) AA 6082-T6 [16]

2.3. Development of correlation using Buckingham pi theorem-

Roy et.al. [18] have developed a correlation for the evaluation of maximum temperature using the Buckingham pi theorem. In this investigation first of all the author has calculated the peak temperature with the help of a three-dimensional mathematical model for different values of welding parameters like angular velocity, Traverse speeds, and three different alloys namely, 304L Austenitic stainless steel, 1018 C-Mn Steel and AA 6061. Then the dimensionless peak temperatures have been plotted on
a graph against heat input in dimensionless form. Hence a mathematical correlation was developed between the peak temperature and heat input. In conclusion, it is observed that the developed correlation has a better agreement with the practical peak temperature values as shown in Fig. 5 with the filled symbols below.

\[ T^* = 0.131 \log_{10}(Q^*) + 0.196 \]

\[ Q^* = \frac{(f \cdot A \cdot \sigma_8 \cdot C_p \cdot \omega)}{K U^2} \]

Where, \( U \) = translational velocity of the tool, \( \omega \) = rotational velocity of the tool, \( C_p \) = specific heat of the material, \( \sigma_8 \) = yield stress of the workpiece at temperature \( (0.8 \cdot T_s) \), \( T_s \) = solidus temperature, \( A \) = area of the tool shoulder = \( \pi \cdot (R_o^2 - R_i^2) \), \( R_o \) = radius of the shoulder, \( R_i \) = radius of the pin, \( K \) = thermal conductivity of workpiece material, \( f \) = ratio of heat generated at tool and workpiece interface to the heat transferred to the workpiece and the tool

\[ f = [ (k \cdot \rho \cdot C_p)_{w}^{1/2} ] / [ (k \cdot \rho \cdot C_p)_{t}^{1/2} ] \]

\[ T^* = 0.131 \cdot \ln(Q^*) + 0.196 \]

2.4. Model using FEA:

In this investigation, the author R Vaira Vignesh et. al. [19] has developed a thermal model using the Finite element modeling technique to analyze the thermal properties in friction stir welding. For the DOE of this proposed model \( 2^k \) factorial design is implemented. First, the author has used the developed model to simulate the work of Hwang et. al. [20] as shown in Fig. 7. In this work, the author has computed the peak temperature values using his model by placing 10 probes at a distance of 5mm and compared his results with the experimental values of peak temperatures found in previous research work as shown in Fig. 7. The heat generation at the interface of the plate surface and the tool’s pin is...
calculated by the Eq.9 and the heat generated between the tool shoulder’s surface and plate surface is determined by the Eq. 10.

\[ Q_{\text{pin}}(T) = \frac{\mu Y(T)}{\sqrt{3(1+\mu)^2}} \]  
(9)

Where, \( Y(T) = \text{Average shear stress as a temperature function} \)

\[ q_{\text{shoulder}}(r,T) = \mu \left( \frac{F_s}{A_s} \right) \text{ or if } T < T_{\text{melt}} \]  
(10) or

\[ q_{\text{shoulder}}(r,T) = 0 \text{ if } T < T_{\text{melt}} \]  
(11)

Figure 7: Comparison of experimental and computed temperature values concerning the probe number situated at a distance of 5cm from each other [19]

2.5. Mathematical model Heat Generation

Tikader et al [21] presented a model for the heat generation and temperature distribution for a cylindrical, flat shoulder cylindrical, and conical tool in friction stir welding. The author used multiple tools with multiple tool designs and speed and found the heat generation and temperature profile during FSW. In this model, the author has calculated the heat as a summation function of all the heat produced during the FSW process due to:

- The heat generated due to Vertical Pressure at the tool pin tip surface \( (Q_1) \)
- The heat generated due to the rotational motion of the tool at the side surface \( (Q_2) \)
- The heat generated due to the traveling motion of the tooltip at the side surface \( (Q_3) \)

The total heat produced in the case of a cylindrical probe is calculated as given by equation 12-15:

\[ Q_p = Q_1 + Q_2 + Q_3 \]  
(12)

\[ Q_p = \pi R_{\text{pl}} H_p V \left( \frac{2}{3} \pi \mu \omega P(R^3_{\text{pt}}) + 2 \mu \pi \tau * \omega R^2_{\text{pl}} H_p + \mu S_{ys} * \pi R_{\text{pl}} H_p V \right) \]  
(13)

The total heat produced in the case of a flat cylindrical shoulder with a conical probe is:

\[ Q_p = \frac{2}{3} \pi \mu \omega P(R^3_{s} - R^3_{\text{pl}}) + \mu S_{ys} * R_s h_1 V + \frac{2}{3} \pi \mu \omega P. R^3_{\text{pl}} + 2 \mu \pi \tau * \omega R^2_{\text{pl}} H_p + \mu S_{ys} * \pi R_{\text{pl}} H_p V \]  
(14)

The total heat produced in the case of a flat cylindrical tool with a conical probe is:

\[ Q_p = \frac{2}{3} \pi \mu \omega P(R^3_{s} - R^3_{\text{pl}}) + \mu S_{ys} * R_s h_1 V + \frac{2}{3} \pi \mu \omega P. (R^3_{s} - R^3_{\text{pl}}) + \]
\[
\left( \frac{2}{3} \pi \mu \omega \tau (R_{pb}^2 + R_{pb} R_{pt} + R_{pt}^2) + \frac{\mu S_{ys} V} {2} (R_{pt} + R_{pb}) \right) \sqrt{\left( R_{pb} - R_{pt} \right) \left( 2 + H_p^2 \right)}
\]

(15)

Where, \(Q\) = Total rate of heat generation, \(Q_p\) = Rate of heat generation in tool probe, \(\mu\) = Coefficient of friction, \(\omega\) = Rotational Speed of the tool, \(R_{pb}\) = Radius of Probe on Shoulder Surface, \(R_{pt}\) = Radius of the Probe tip, \(R_s\) = Radius of Shoulder, \(H_p\) = Height of probe, \(S_{ys}\) = Yield Strength of the work material, \(V\) = Traverse Speed of the tool.

This work also elaborates on the thermal analysis model of the weld zone during friction stir welding. A three-dimensional finite element transient thermal model is presented for analysing the temperature distribution and heat generation during FSW. It is observed that the developed model gives the better prediction which are consistent with the experimental results as shown in Fig. 8 and Fig 9.

Figure 8: a) Comparison between the Experimental and Predicted values of temperature b) Comparison between peak temperature with varying probe diameter [21]

Figure 9: Comparison of Temperature distribution during FSW at distances perpendicular to the direction of weld [21]
2.6. Thermal Modelling Using Calculated Young’s Modulus Values-

Meghyani et al. [22] presented a mathematical formulation for thermal modeling of workpieces during the FSW process using MATLAB and ABAQUS software. The work used the values of calculated Young modulus values of the workpieces to find the temperature of the weld pool. The method utilized Coulomb’s Friction law and Johnson-Cook Law using FEM and ALE models to find the temperature of the weld pool. The yield stress was evaluated using the Johnson-Cook formula as given in Eq.16:

\[ \sigma_y = [A + B(\varepsilon_p)^n [1 + C(\varepsilon_p/\varepsilon_0)].[1 - [(T_W - T_{ambient})/(T_{melting} - T_{ambient})]^{m}]] \]  

(16)

The Values of Young modulus were later found using FEM models and were incorporated into the ALE models to find the temperature variations in the weld pool. The comparison between the experimental and the predicted values of temperatures are given in Fig 10. It can be seen from the results the model predictions are quite consistent with experimental measurement.

![Figure 10: Comparison of Predicted and experimental values of Temperature of Weld pool during FSW [22]](image)

2.7. Arbitrary Lagrangian-Eulerian (ALE) Based model

Salloomi et al. [23] presented an Arbitrary Lagrangian-Eulerian Modeling based model intended for modeling the three-dimensional equation for FSW of AA 7075-T651 for analyzing Heat generation, temperature profile, and stresses induced. For the verification of the model, the author used an experimental setup with Thermocouples and dynamometer, which were later compared with the values predicted by the ALE model. The governing equations used for the modeling are as follows:

\[ Q + \nabla \cdot (K \nabla T) = cp \frac{\partial T}{\partial t} \]  

(17)

\[ Q_{frictional} = \mu \cdot p \cdot \gamma \]  

(18)
The yield stress was modelled using the Johnson-Cook equation:

\[
\sigma_y = [A + B(\varepsilon_P)^n][1 + C(\varepsilon_P/\varepsilon_0)][1 - ((T - T_{ambient})/(T_{melting} - T_{ambient}))^m]
\]  

Figure 11: Temperature profile a) across the plate during FSW b) Comparison of numerical and experimentally measured temperature profile [23]

2.8. Heat Generation During Friction Stir Welding Process-

Durdanovic et al. [24] presented an analytical model which gives the total thermal energy provided to weld joints based on the heat provided to the different phases during FSW: Dwelling, Plunging, Welding, and Pulling out. He formulated that the heat is provided to overcome the adhesion (Pure sticking) and for deformation (Pure sliding). The thermal energy can thus be calculated by the summation of both these energies. The equations given in this study are based on Sticking and sliding energy. According to the proposed model, Thermal energy can be calculated by Using equation 22-24.

\[
Q = Q_{adhesion} + Q_{deformation}
\]

\[Q = Q_{PT} + Q_{PS} + Q_{St}\]  

\[\delta = \frac{\nu_{cp}}{\nu_{\omega}}\]  

\[Q = \delta \cdot Q_{sticking} + (1 - \delta)Q_{sliding}\]

Where, \(Q = \text{Total Thermal Energy}, Q_{adhesion} = Q_{sticking} = \text{Energy for overcoming Adhesive force}, Q_{deformation} = Q_{sliding} = \text{Energy for deformation of the material}, \delta = \text{Contact State Variable}, \nu_{cp} = \text{Velocity of Contact points in contact with the tool}, \nu_{\omega} = \text{Rotational Velocity of the tool}.

3. Conclusions

The temperature analysis and heat generation modeling of friction stir welding have unforeseen and vast implications as they can be used in a variety of applications. They can be used to study and predict the microstructure of the weld material and can also be used for stress analysis, and for preventing the defects and distortions in the weld material. There are different models such as FEM, Numerical, and Analytical models based on the tool and weld parameters which may be used for prediction as well as a research tool and may also be used in industries for preventing material, and economic losses.

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