Manufacturing Process Optimization: Three-Dimensional Heat Transfer Analysis of Friction Stir Welded Joints

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***Abstract*—In modern manufacturing engineering, producing lightweight high-performance components with optimal joint integrity is vital for the aerospace and automotive sectors. Friction Stir Welding (FSW) has emerged as a disruptive solid-state joining technology that enhances production efficiency by eliminating conventional fusion defects such as porosity and hot cracking, while significantly reducing operational costs through the avoidance of filler materials and post-weld finishing. Controlling the localized thermal cycle during FSW is critical to optimizing process variables, governing material flow, and preventing tool wear. This paper introduces a three-dimensional finite element analysis (FEA) model developed in ANSYS to simulate transient heat transfer and predict temperature distribution within the workpiece. To ensure process modeling accuracy, the numerical framework integrates simultaneous thermal contributions from both the tool shoulder and the tool pin interfaces. The simulated thermal histories show close agreement with multi-model experimental data, demonstrating that this numerical approach serves as a robust engineering tool to evaluate thermal cycles and accelerate production setup optimization in industrial applications.**

***Index Terms*—Friction stir welding, heat transfer, finite element analysis, temperature distribution.**

I. Introduction

FSW was invented at the Welding Institute (TWI) of UK in 1991[1]. As shown in figure 1, a non-consumable rotating tool with a specially designed pin and shoulder is inserted at the faying edges of the plates to be welded and traversed along the joint.

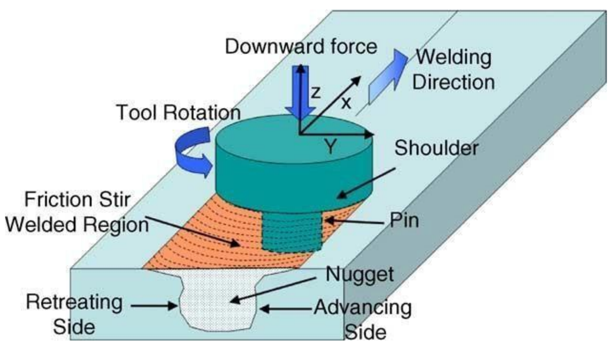


Figure 1. Schematic drawing of friction stir welding

The two plates are fixed together by means of clamps on the bed and vertical force is applied by fixing the tool on the collet of vertical milling machine. The friction between the tool and the work piece leads to plastic deformation of work piece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of pin. FSW has been proven to be very successful joining technology for aluminum alloys. It can even weld dissimilar metals like aluminum with steel. This new technique is being successfully applied to aerospace, automobile and shipbuilding industries [2] and is attracting more and more research interest.

The heat transfer process is one of the most important aspects in the FSW study. A good understanding of the heat transfer process in the work piece can be helpful in predicting the thermal cycles in the welded work piece and the hardness in the weld zone; subsequently can be helpful in evaluating the weld quality. A known temperature distribution is also important for calculating the temperature dependent viscosity when modeling material flow.

Chao and Qi [3,4] published a three-dimensional heat transfer model in which a constant heat flux input from the tool shoulder/work piece interface was assumed and a trial-and-error procedure was used to adjust the heat input until all the calculated temperatures matched with the measured ones. Figard, Ground and Middling [5,6] developed a process model for FSW in which heat input from the tool shoulder was assumed to be the frictional heat and the coefficient of friction.

Originally developed and patented by The Welding Institute (TWI) in Great Britain in 1991, Friction Stir Welding (FSW) represents a groundbreaking advancement in manufacturing technology. The core method utilizes a specialized, non-consumable rotating tool that resists wear during operation (p. 2). This cylindrical tool features a specially engineered pin extending from a wider cylindrical shoulder. During operation, the machine forces this rotating tool to plunge directly into the abutting joint line of rigidly clamped base workpieces. Intense mechanical friction at the interface, combined with severe plastic deformation of the metal, together generate severe localized heating.

This highly localized heating efficiently softens the adjacent material without ever reaching its actual melting point. As the system progresses, the combined tool rotation and forward translation mechanically move this highly plasticized material directly behind the moving tool. This continuous stirring and forging action create a high-integrity, solid-state, and entirely defect-free seam along the joint. Because it bypasses liquid melting entirely, FSW successfully eliminates traditional fusion welding anomalies like solidification cracking, gas porosity, and elemental dilution. Consequently, it successfully joins difficult lightweight alloys—such as high-strength aluminium—and otherwise incompatible dissimilar material combinations. Heavy industrial sectors like aerospace engineering, automotive manufacturing, and commercial shipbuilding widely adopt this technique to fabricate high-strength structural components.

Within this automated process, precise thermal management directly determines final component quality and overall production throughput .Implementing advanced predictive thermal cycle modeling allows engineers to strictly control localized material microstructures. This predictive approach accurately evaluates localized hardness boundaries and resulting ultimate tensile strengths across the weld zones. Developing accurate, real-time temperature profiles helps engineers establish precise operating parameters for highly automated robotic manufacturing systems. Early academic research by Chao and Qi significantly simplified these equations by assuming a uniform, simplified shoulder heat distribution. Later, Figard et al. adjusted analytical friction factors to more realistically prevent simulated melting. Modern numerical models, such as Computational Fluid Dynamics (CFD), successfully map complex plasticized material flow behaviour around the tool geometry.

However, traditional models overlooked pin-boundary heat generation profiles. Neglecting tool pin friction limits simulation accuracy for thick sections (p. 3). This paper introduces an integrated process-driven three-dimensional heat transfer model. The framework models total heat output by combining pin and shoulder interactions . This provides manufacturing engineers with a reliable virtual setup verification tool.

friction or the calculated temperature during the welding was adjusted to keep the calculated temperature from exceeding the material melting point. The Rosenthal equation for modeling the heat transfer in thin plates has also been applied in modeling the heat transfer in FSW [7]. Zahedul, Khandkar and Khan [8] modeled the heat transfer for overlap friction stir welding with finite element method where a moving heat source was used. Bendzak, North and Smith [9,10] applied the computational fluid dynamics method (CFD) in modeling the heat and material flow process for FSW.

In the above mentioned models, the heat input from the tool shoulder is the only heat input, the heat generated at the tool pin/work piece interface has not been included. In order to model the heat transfer process accurately, it is necessary to include the heat generatedby tool pin in the modeling. Schmidt, Hattel and West [11] established analytical model for heat generation by FSW, based on different assumptions of the contact

In this paper, a three dimensional heat transfer model has been developed. The simulation results are compared with the experimental data of various research papers. To maintain consistency, the dimensions of the work piece, material properties, radius of the shoulder and pin, length of pin, rotational speed and translational speed were kept same as mentioned in experimental data of various research papers.

II. Numerical Modeling of FSW

In FSW, heat is transferred to the work piece and tool body by conduction. This increases the heat content of the work piece and tool and rest of the heat is transferred to the ambient air by convection. Heat transferred by radiation can be neglected, as the maximum temperature is less than 500 conditions imposed during FSW.

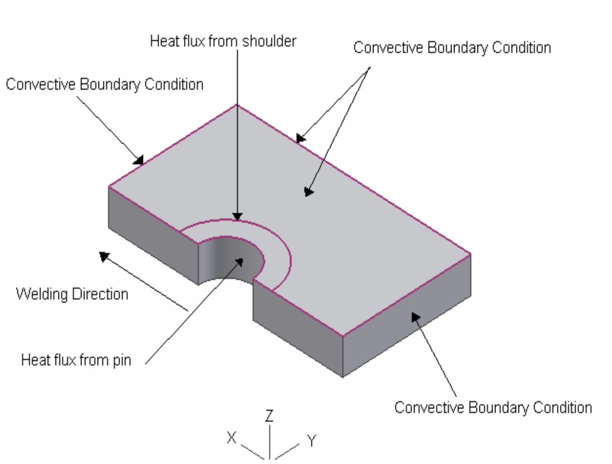


Figure 2. Boundary conditions

for aluminum alloys. Figure 2 shows boundary

The frictional heat generated is divided into two parts, one at the tool pin/material interface and other at the tool shoulder/material interface. In case of butt welding using a moving heat source, the temperature at any point of work piece changes with time. The temperature of the point under consideration increases as the heat source comes near it, reaches a maximum value when the heat source is nearest to the point and then finally decreases as time passes. The governing equation for transient state three dimensional heat conduction for welding in x-direction is given as condition between rotating tool surface and the work piece. Ulysse [12] has established three dimensional

finite element method (FEM) model to predict the temperature and tool force in FSW. The heat generated was equated to the product of stress and strain in the material.

Details of the heat transfer equation in a moving coordinate system can be found in reference [13]. The heat flow should satisfy the above equation and also the boundary conditions shown below.

$$T = T_o \text{ at } S_1 \text{ and}$$
$$k\,\partial T/\partial n + hT + q = 0 \text{ at } S_2 \quad (2)$$

where n is the normal direction vector of boundary T, his the convective heat transfer coefficient, q is the heat flux into the surface or coming out of the surface and S_1 and S_2 are the portions of the boundary on which these boundary conditions are specified as shown in figure 2.

III. Model Description

The FSW process is divided into following three periods:

1. The penetrating period is from the instant when the tool pin contacts the work piece surface until the tool shoulder contacts the work piece surface.

2. The welding period is from the instance when the tool shoulder contacts the work piece until the tool stops traversing. This period is the main period of welding.

3. The pulling up period is from the instance when the tool starts pulling out until the pincompletely leaves the work piece.

The following assumptions are introduced to simplify the model.

1. All the frictional energy is converted to heat andexerted on the work piece.
2. The material deformation at the work piece topsurface during the weld is negligible.
3. The tool pin is of the shape of cylinder.
4. Heat is being continuously generated at the tool pin and shoulder interface (Heat flux boundary condition).

5. Heat is lost to ambient air by natural convectionat four faces of the heat flow model (convective boundary condition).

6. To minimize computations only one plate is modeled and the heat flux at the faying surfaces is made zero (symmetric boundary condition).

7. The face in contact with the fixture (bottom face) is given suitable convective coefficient, as the contact resistance is not known.

8. The torque required to rotate a circular shaft relative to the plate surface under the action of an axial load is given by 14]:

where M is the interfacial torque, μ is the friction coefficient, R is the shoulder radius, and P is the pressure distribution across the interface. If all the shearing work

$$\int_0^{M_R} dM = \int_0^R \mu P(r) 2\pi r^2 dr = \frac{2}{3}\mu\pi P R^3 \quad \text{-------(3)}$$

at the interface is converted into frictional heat, the average heat input per unit area and time becomes:

$$Q_1 = \int_0^{M_R} \omega\, dM = \int_0^R \omega 2\pi\mu \mathrm{P} r^2\, dr \quad \text{--(4)}$$

where Q1 is the net power [W] and is the angular velocity [rad/s]. By substituting =2 N, into equation (4), we get,

$$Q_1 = \int_0^R 4\pi^2 \mu P N r^2 dr = \frac{4}{3}\pi^2 \mu P N R^3$$ ---------- ---(5)

From equation (5) it is obvious that the heat input depends both on rotational speed and the shoulder radius, leading to a non-uniform heat generation during welding.

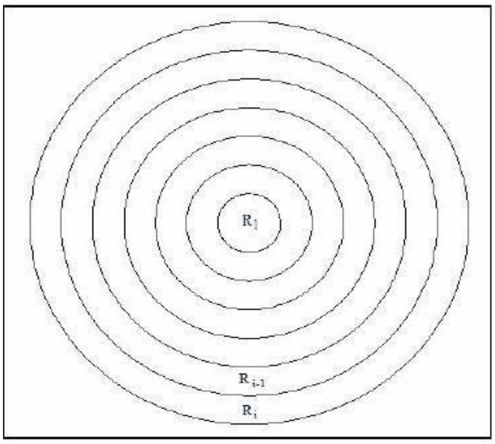


Figure 3. Subdivision of the tool shoulder into a series of volume elements of varying strength.

n order to describe the heat source in the numerical model it is more convenient to express the heat generation as a sum of individual contributions:

$$Q_1 = \frac{4}{3}\pi^2 \mu P N \sum_{i=1}^{n} (R_i^3 - R_{i-1}^3)$$ --(6)

where R_i and R_{i-1} are defined in figure 3.

Hence energy generated from position R_i to R_{i-1} is equation

--(8) $$\Delta Q_1 = \frac{4}{3}\pi^2 \mu P N (R_i^3 - R_{i-1}^3)$$

Heat flux q_1 which is heat flow per unit area of the shoulder can be calculated by Chao and Qi [3]:

--(9) $$q_1 = \frac{3 \cdot Q_1 \cdot r}{2\pi(r_S^3 - r_P^3)} \text{ for } r_P \le r \le r_S$$

The heat generation increases as the distance from the center increases. However, for simplicity a uniform distribution of heat across the surface of the shoulder is assumed. Hence for uniform distribution

$$r = \frac{R_S + R_P}{2}$$

P. Colegrove [15] estimated that the heat generation by pin is 20 % of the heat generated by shoulder. Hence, $q_2 = 0.2\ q_1$ -- (11)

IV. Material Properties and Boundary conditions for validation

Thermal conductivity k and heat capacity c are dependent on temperature. The ambient temperature is assumed to be 32ºC. The initial temperature of the workpiece is assumed to be equal to the ambient temperature. A convective coefficient of 30 W/m^2 ºC is applied as a boundary condition at the top of work piece and 15 W/m^2 ºC on the side surface of work piece. As the value of conductive coefficient between the work piece and backing plate is not known, a higher convective coefficient of 300 W/m^2 ºC is applied as a boundary condition to the bottom of the work piece. The welding speed is input to the model as mass transport velocity inx – direction. Heat flux is applied at the pin surface and shoulder surface at the top of the work piece. These values were taken as boundary condition by most of there searchers [3,8,14]. Finite element software ANSYS issued for the analysis. Solid 70 which is a three dimensional thermal solid, is used as the element. Solid70 has three- dimensional thermal conduction capability.

The element has eight nodes with a single degree off freedom, temperature at each node. The element is applicable to a three- dimensional steady state or transient thermal analysis.

V. Comparison of Various models and its Validation

Experimental data of various researchers were compared with numerical results to validate the mod

1. Model Validation-1

Friction stir welding of aluminum alloy 2195 was simulated in ANSYS and compared with the results of Chao [3]. To maintain consistency, the dimensions of the work piece, material properties, radius of shoulder and pin, length of pin used were same as Chao. The workpiece had dimensions 610 mm in length, 204 mm inwidth and 8.1 mm in height. The tool had a shoulder radius of 12.7 mm, pin radius of 5.0 mm and pin lengthof 7.6 mm. A rotational speed of 240 rpm and a translational speed of 2.36 mm/sec were used for carrying out the simulation. The material properties of aluminum alloy 2195 are given in table 1[16].

Table 1. Variation of material properties of aluminum alloy 2195 with temperature

Temperature ºC	Thermal conductivity (W/m ºC)	Specific heat (J/kg ºC)
0	87	835
50	100	910
100	108	945
150	120	1000
200	130	1050
250	140	1085
300	145	1100

A block of 0.61 x 0.204 x 0.0081 m was constructed in ANSYS. Thermal conductivity and specific heat were given as input to the element as a function of temperature. A value of 2.77 kg/m^3 for aluminum alloy is given input as density. Coefficient of friction for analytical calculation is taken as 0.3[3].Since the model is symmetrical along the axis, only halfthe model is prepared. After meshing convection is applied on the side, top and bottom surfaces and heatflux is calculated analytically and applied at the pin surface and top surface of shoulder area. Figure 4 shows the temperature obtained in the work piece at a distance of 305 mm from start of welding. As shown in figure 5, the results match with the experimental data, whichshows the validity of the model.

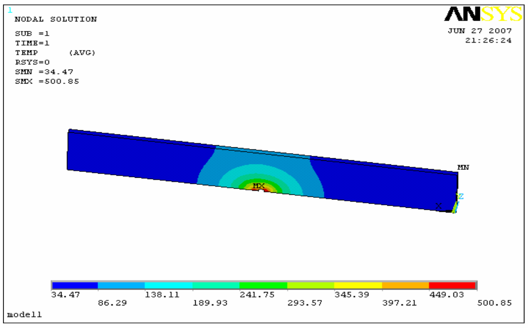


Figure 4. Temperature distribution along the work piece for model

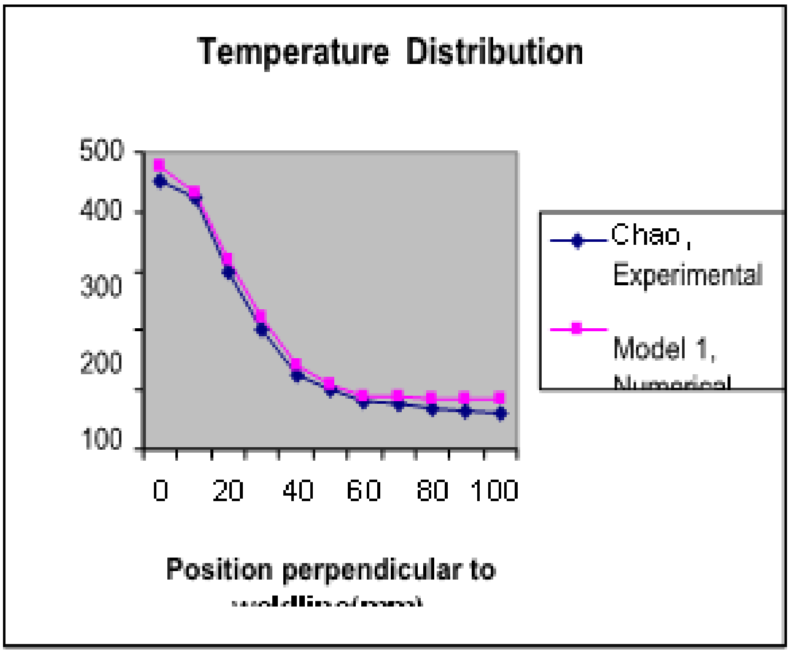


Figure 5. Comparison of experimental and Numericaldata for model 1

2. Model Validation-2

Table 2. Variation of material properties of aluminumalloy 6061 with temperature

Temperature°C	Thermal conductivity (W/m °C)	Specificheat J/ (kg °C)
37.8	162	945
93.3	177	978
148.9	184	1004
204.4	192	1028
260	201	1052
315.6	207	1078
371.1	217	1104
426.7	223	1133
571.1	253	1230

The results of simulation are in good comparison with xperimental results as shown in figure 7.

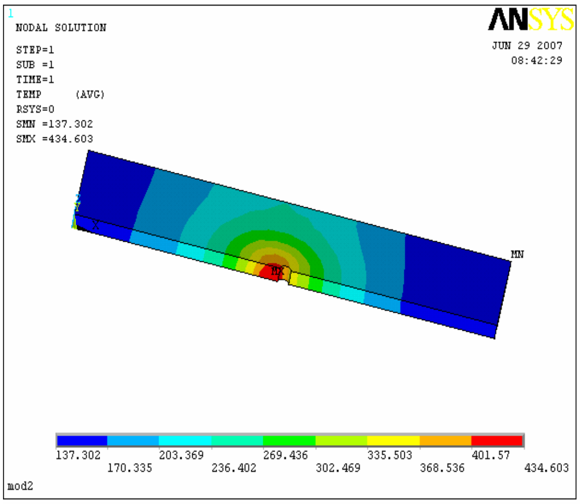


Figure 6. Temperature distribution along the work piece for model 2

Friction stir welding of aluminum alloy 6061 was simulated and compared with the results of Vijay Soundarajan [17]. The work piece had dimensions of200mm in length, 100 mm in width and 6.4 mm in height. The tool had a shoulder radius of 12.0 mm, pin radius of 2.6 mm and pin length of 5.9 mm. A rotational speed of 344 rpm and translational speed of 2.2 mm/sec were used for carrying out the simulation. A value of
2.77 kg/m^3 was used for density. Figure 6 shows the temperature distribution at the distance of 100 mm from the start of welding. The material properties of aluminumalloy 6061 are given in table 2 [16].

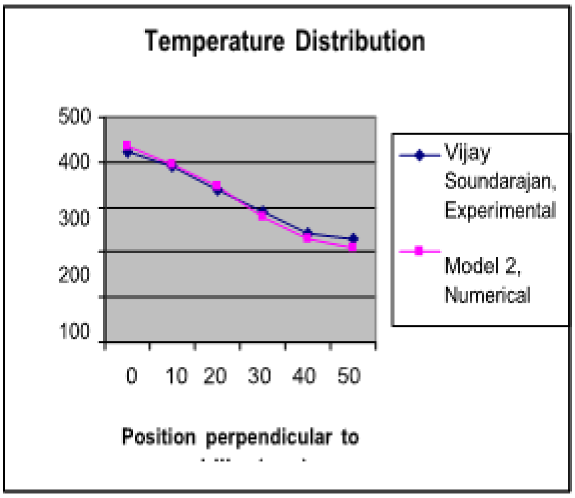


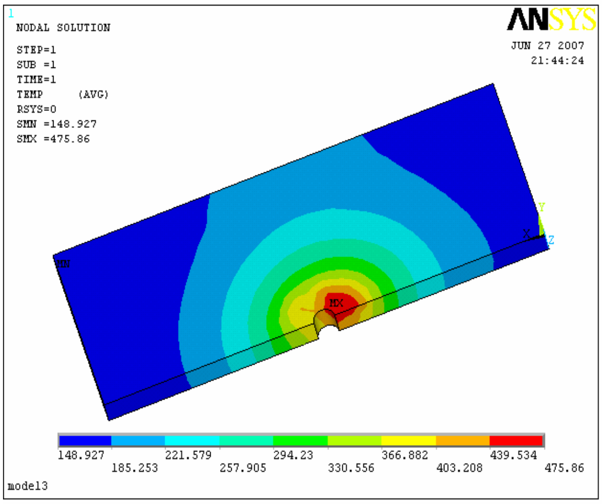
Figure 7.
Comparison of experimental and Numericaldata for model 2

3. Model Validation-3

Friction stir welding of aluminum alloy 6061 was simulated and compared with the results of M.

Song and R.Kovacevic [18]. The work piece had dimensionsof 254 mm in length, 102 mm in width and 12.7 mm in height. The tool had a shoulder diameter of 50 mm and pin diameter of 12 mm. The rotational speed and translational speed were

914 rpm and 3.18 mm/sec respectively. Figure 8 shows temperature distribution at adistance of 127 mm from the start of welding. The resultsof simulation are in good comparison with experimental results as



shown in figure 9.

Figure 8. Temperature distribution along the work piecefor model 3

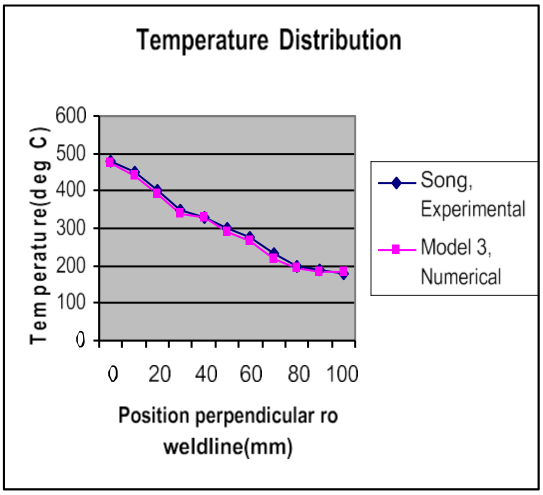


Figure 9. Comparison of experimental and Numericaldata for model

VI. Results and Discussion

The nature of curves in figures 5, 7 and 9 shows that the variation of temperature along the length of work piece for experimental and numerical results are more or less same. Figures 4, 6 and 8 indicate that the calculated temperature distribution at a distance of approximately 20 mm away from the weld interface confirm to similar peak as in experimental results. It clearly indicates that high temperature isotherms are denser in front of the tooling the direction of its advancement i.e. weld velocity in- direction. The temperature of the plate away from the weld interface reduces rapidly. Also temperature gradient exists in the thickness direction along the tool pin work piece interface. This is primarily due to greater amount of frictional heat caused along the tool-shoulder interface compared to the same along the tool pin work piece interface. Hence, the portion of the work piece immediately beneath the tool shoulder towards the advancing side shows maximum heat.Conclusion

A three-dimensional heat conduction analysis is carried out using finite element method to understand the process of heat transfer and resultant temperature distribution around the weld interface during friction stir welding by comparing the numerical results with experimental results. Three different models were considered and the results are compared. The basic conclusions that can be drawn from the present investigations are the following:

1. Friction stir welding is a new solid state welding process, which uses frictional heating to plasticize the material and join it.
2. The 3-D numerical heat flow model yields a temperature distribution along the work piece that is consistent with that observed experimentally by various researchers.
3. Numerically obtained thermal cycles can be of significant help in understanding the weld thermal cycles expected to be experienced by weld interface in friction stir welding process.

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