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Investigations on temperature distribution in welding of Aluminium alloys to steel using FEM

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This research study focuses on the objective to establish an analytical model for determining the thermal distribution during friction stir welding (FSW), based on different assumptions of the contact condition between the rotating tool surface and the weld piece. The material flow and heat generation are characterized by the contact conditions at the interface, and are described as sliding, sticking or partial sliding/sticking. The analytical expression for the heat generation is a modification of previous analytical models known from the literature and accounts for both conical surfaces and different contact conditions. Aluminium metal matrix composites and steel 304 (dissimilar material joining) is being used for this study. Three dimensional Finite Element Models have been developed to visualize the temperature distribution across the butt ends of the plates. The results are validated with the experimental results reported in the literature. The result reveals that there exists a good coherence between experimental and simulated results.

KEYWORDS: Friction Stir Welding, Aluminium MMC, Steel 304

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1 Introduction: Aluminium MMCs are finding greater utility in automobile and aerospace industries. Significant features of Al MMCs that draws huge attention are summarised as follows: considerable reduction in mass, prominent in engine parts, enhanced material properties, in particular strength and stiffness, improved lubrication characteristics and wear resistance, reduced thermal expansion coefficient. This positive facet of Al MMCs increases component durability and permits application in extreme service conditions. To boost up the application of aluminium MMCs in real time applications, it is essential to weld these specimens to other engineering materials, such as steel.

The operations during FSW consist of several phases of action—each phase can be described as a time period where the welding tool and the work piece are moved relative to each other. In the first operation, the tool is plunged vertically into the joint line between the work pieces, while the tool is rotating. This action takes place in the plunge period. The plunge period is followed by the dwell period, where the tool is held steady relative to the work piece but still rotating. The mechanical interaction, due to the velocity difference between the rotating tool and the stationary work piece, produces heat by frictional work and material deformation. This heat dissipates into the surrounding material, the temperature rises and the material softens. After these two operations the actual welding process can be initiated by moving either the tool or the work piece relative to each other, along the joint line. The traverse velocity is in the range of 1–10mms−1 depending on welding parameters, i.e. rotation speed, plunge force or plunge depth and tilt angle, but also tool design and weld piece properties. When the weld distance is covered, the tool is pulled out of the work piece leaving behind an exit hole as a footprint of the tool. A schematic representation of the set-up is illustrated in figure 1.

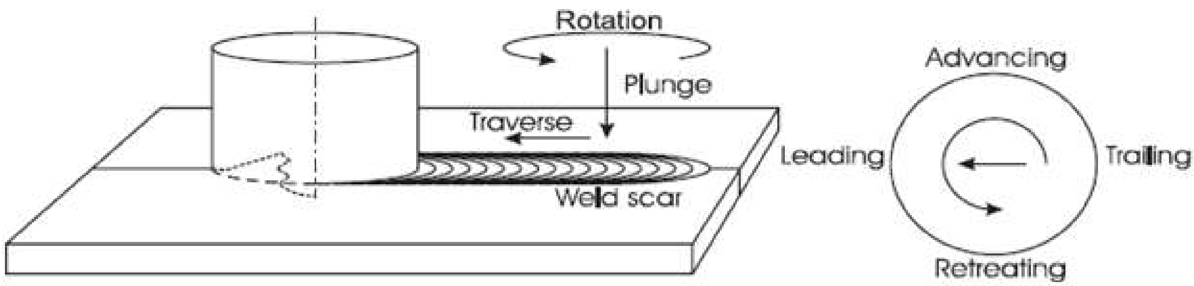


Figure 1: Schematic of the weld set-up and definition of orientations

The difficulty of making high-strength, fatigue and fracture resistant welds in aerospace aluminium alloys and steel has constrained the wide use of welding for joining aerospace structures. These alloys are generally classified as non-weld able because of the poor solidification microstructure and porosity in the fusion zone. Besides, the loss in mechanical properties compared to that of the base material is very significant. These factors make the joining of these alloys by conventional welding processes unattractive. However, FSW appears to be an effective solution this intricacy. There has been several research works reporting the lacuna's in arc welding of dissimilar aluminium/steel joints viz., preferential melting of the aluminium alloy and formation of brittle iron-aluminium intermetallics. However, friction stir welding process illustrates positive sign for its employment to join dissimilar aluminium/steel. Conversely, intermetallic formation is still of concern.

The literatures pertaining to joining of dissimilar materials especially for the ones focusing on Aluminium metal matrix composites and steel is inadequate. The vital research reports contributing to this research are briefed in this section.

It was repeatedly observed that during FSW process, the material undergoes intense plastic deformation at elevated temperature that generates fine and equiaxed recrystallized grains. The fine microstructure in friction stir welds results in enhanced mechanical properties **[1-4].** Benavides et al. **[5]** investigated the effect of the workpiece temperature on the grain size of FSW 2024Al. It was observed that while decreasing the starting temperature of work piece from 30 to -30^{0}C with liquid nitrogen cooling resulted in a decrease in the peak temperature from 330 to 140^{0}C at a location 10 mm away from the weld centerline, thereby leading to a reduction in the grain size from 10 to 0.8mm in FSW 2024Al. Following the same approach, Su et al. **[6]** prepared bulk nanostructure 7075Al with an average grain size of100 nm via FSP, using a mixture of water, methanol and dry ice for cooling the plate rapidly behind the tool.

Salem et al. **[7]** investigated the effect of FSW on the microstructure and superplasticity of a superplastic 2095 sheet. It was reported that the dynamically recrystallized 2095 SP sheets were successfully friction stir welded at 1000 rpm and welding speed of 3.2 and 4.2 mm/s, with fine-grained microstructure formed in the weld nugget. Superplasticity was retained after FSW and increased with increasing welding speed. This demonstrates that FSW is an effective technique to join superplastic alloy plates/sheets while retaining super plasticity. Sterling et al. **[8]** reported that in quenched and tempered

C–Mn steel, FSW resulted in decrease of hardness in the weld nugget and tensile properties, with fracture occurring at the HAZ. However, the as-welded strengths of FSW C–Mn steel were superior to those observed in GMAW using ER100S-1 filler metal.

The improvement in the FCP properties after FSW was further verified in FSW 2519Al-T87 and 2024Al-T351 by Pao et al. **[9]** and Bussu and Irving **[10].** Pao et al. **[9]** reported that the nugget zone and HAZ of FSW 2519Al-T87 exhibited lower fatigue crack growth rates and higher fatigue crack growth threshold, DKth, at bothR = 0.1 and 0.5, in air and in 3.5% NaCl solution, compared to the base metal. Furthermore, the FCP properties of the nugget zone were higher than those of the HAZ. Compared to the fatigue crack growth rates in air, the fatigue crack growth rates in 3.5% NaCl solution for the base metal, HAZ, and nugget zone, in the intermediate and high DK regions, were about two times higher than those observed in air.

There are very few literatures reporting FEA being employed for FSW of dissimilar materials. Moreover, the papers still have not highlighted the fundamentals and the process progression making it difficult for readers to follow. One of the manuscript dealing with FEA for FSW is discussed briefly.

Song and Kovacevic **[11]** investigated the influence of the preheating/dwell period on the temperature fields. They assume a sliding condition and used an effective friction coefficient and experimental plunge force in the heat source expression. The objective of this work is to estimate the heat generation based on assumptions for different contact conditions at the tool/matrix interface in FSW joints. One major difference comparing the present model with previous models known from literature is the flexibility included in the analytical description, both with respect to the contact condition, e.g. sliding/sticking and tool design, e.g. conical surfaces and threads. Second, using the analytical model in comparison with the experimental result estimates which contact condition will be present at the tool/matrix interface.

2 Application of Finite Element Analysis to Friction Stir Welding: The analytical study of any physical phenomenon engrosses two foremost tasks viz., the mathematical formulation of the physical process and the numerical analysis of the modelled process of system. The mathematical formulation of a physical process requires good background knowledge in the related subjects and most often, in using mathematical tools. Development of the numerical model of a process is attained through assumptions concerning functioning of a process. The finite element method is a potential numerical technique devised to evaluate intricate physical processes.

The method is characterized by three features [Eager, T.W. (1990].

1. The domain of the problem is represented by a collection of simple sub domains called finite elements. The collection of finite elements is called the finite element mesh.
2. Over each finite element, the physical process is represented using appropriate functions of desired type, and algebraic equations relating physical quantities at selective points, called nodes.
3. The element equations are assembled using continuity and/or balance of physical quantities. In the process of friction stir welding, heat flows into the material being joined and sometimes may cause serious metallurgical changes in the welded structures, which, in turn, may lead to the early failure of the component. Study of thermal cycles will be the basis for many other analyses like prediction

of distortion and residual stresses, metallurgical analysis etc. Hence, the study of temperature distribution in the parts being welded in case of friction stir welding is imperative. With the developments in computing field and advances in numerical techniques like finite element methods, it is feasible to analyze complicated configurations and loadings which diverge with respect to location and temperature or functions of time for any given weldment. The FEM based analysis is espoused for analyzing the friction stir welding process, since it is a field based phenomenon. Computer based simulations offer the possibility to examine different aspects of the process without having a physical prototype of the product. In this work, main parameters of the friction stir welding process are considered and the finite element simulation is performed using ANSYS. The procedure adopted to access the temperature distribution in ANSYS is illustrated in figure 2.

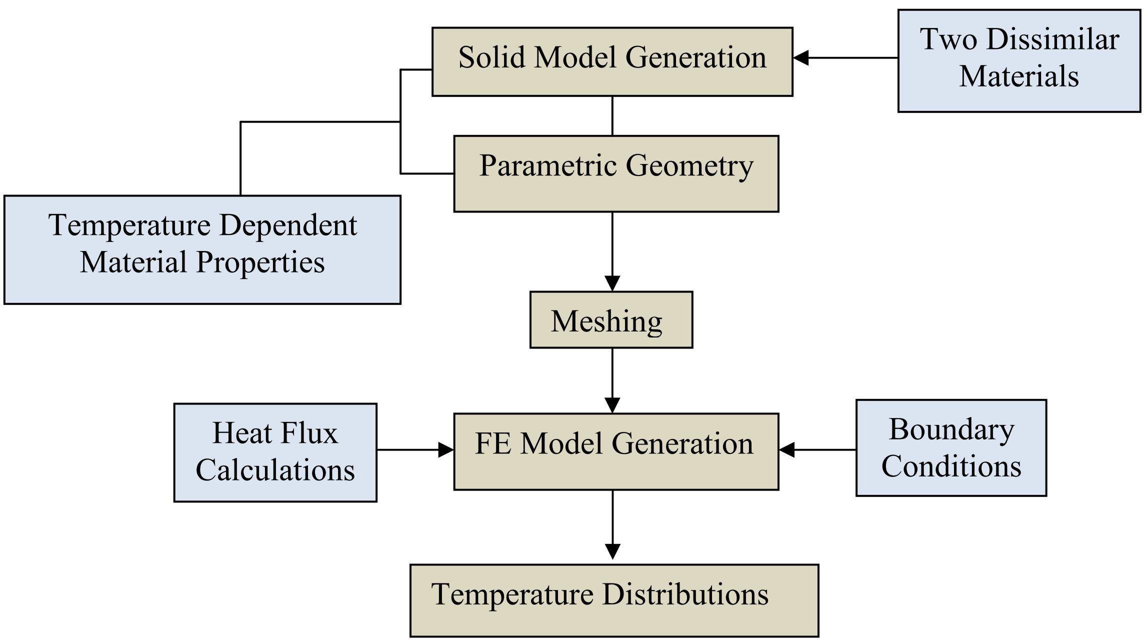


Figure 2: Procedure for thermal analysis.

3. Details of Three-dimensional Model Development: The model for finite element analysis can be built using any of the two techniques viz.,

1. Solid modelling technique
2. Direct generation technique.

The plate is modelled using solid 70. The thickness of all the specimens is 10mm each, respectively. The length of each specimen is approximately 500 mm. The input parameter for the three-dimensional model is chosen for a weldment obtained in **[12]** as it illustrated good bonding as observed from visual inspection. The length used for the calculation by FEM is 80 mm, because the heat affected zone of friction stir welded joint is very short. In addition, a quarter section of the joint is used for the calculation because of the axial symmetry of the joint. A free mesh is adopted for the calculation which includes a total of 75 675 nodes and 24 998 elements for the calculation domain as shown in Figure3. The calculation domain is increased and selected through a series of calculations for this size, which shows a uniform distribution of heat flux.

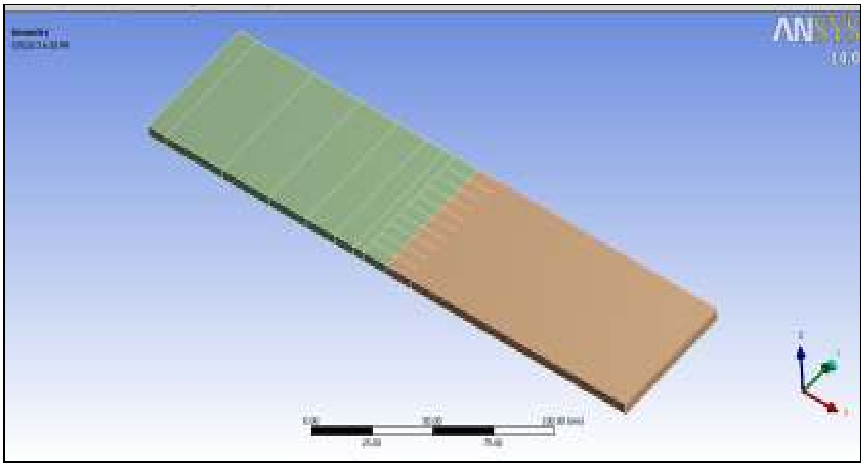


Figure 3: Meshing of the model

4 Material Properties: The material used for the study is Aluminium alloy and steel. The material properties viz., thermal and mechanical properties of the joint aluminium alloy and steel material is used for the numerical analysis.

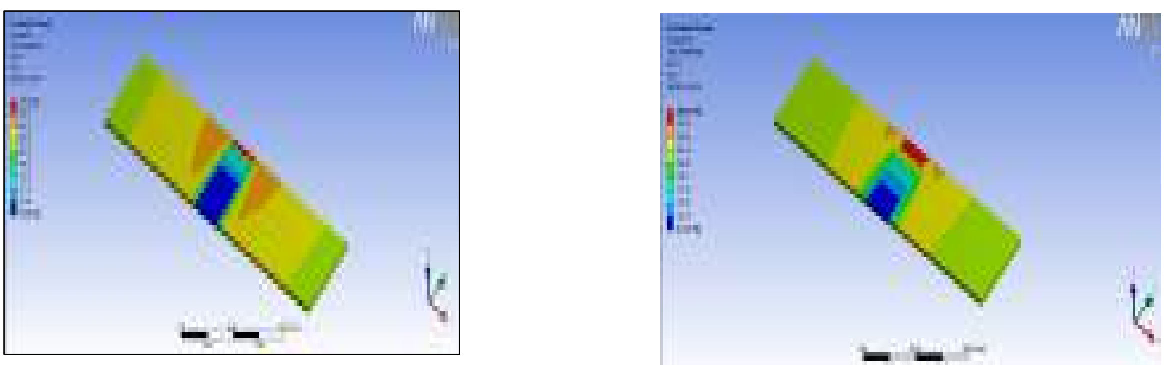


Figure 4: Temperature distributions during Friction stir welding process varying with time as indicated by FEA.

4. Boundary Condition and Heat Input: For this study, an assumption is made that the friction welding process is carried out at room temperature with air as the medium in the set up. The necessary mathematical equations for the FEA are adopted here.

4.1. Control equation in a moving coordinate: During the main friction stir welding process, or the weld period, the tool is moving at a constant speed along the joint line. For such a problem, it is convenient to use a moving coordinate system that moves with the tool, instead of using a stationary system. By applying a moving coordinate, it is not necessary to model the complicated stir process near the pin, thus it makes the model easier. The heat transfer control equation for the work piece in a moving coordinate system with a positive x-direction moving tool can be written as:

$$\frac{\partial(\rho\ c\ T)}{\partial\ t} = \frac{\partial}{\partial x}(k_x\frac{\partial T}{\partial\ x}) + \frac{\partial}{\partial y}(k_y\frac{\partial T}{\partial\ y}) + \frac{\partial}{\partial z}(k_z\frac{\partial T}{\partial\ z}) + v_w\frac{\partial(\rho c T)}{\partial x} \quad (1)$$

Where T is the temperature, c is the heat capacity, r is the density, k is the heat conductivity, and v is the tool moving speed.

4.2. Heat generation: In the presented model, the heat at the tool shoulder/workpiece interface and the heat at the tool pin/work piece interface are both considered.

4.2.1. Heat input from the tool shoulder: The heat generated at the tool shoulder/work piece interface is assumed the frictional work in this model. The local heat generation can be calculated by the following expression:

$$q_{f\,i} = 2\pi\mu F_n R_i n \quad \text{--------------(2)}$$

Where *Ri* is the distance from the calculated point to the axis of the rotating tool, *n* is the rotational speed of the tool. The coefficient of the friction is believed to vary during the FSW process; the detail of the variation is still not clear so far. An effective coefficient of friction is assumed in this model.

2.3. Boundary conditions and initial condition:
2.3.1. Tool shoulder/workpiece interface. The heat flux boundary condition for the workpiece at the tool shoulder/workpiece interface is -

$$k\frac{\partial T}{\partial n}\bigg|_{\Gamma} = q_S \quad \text{-----------------(3)}$$

4.3. Tool pin/work piece interface: The heat flux boundary condition at the tool pin / work piece interface is similar to the tool shoulder / work piece interface, and can be written as:

$$k\frac{\partial T}{\partial n}\bigg|_{\Gamma} = q_P \quad \text{--------------------(4)}$$

qs and *qp* can be calculated by Eqs. (2) and (3).

4.3.1. The convection boundary conditions: The convection boundary condition for all the workpiece surfaces exposed to the air can be expressed as:

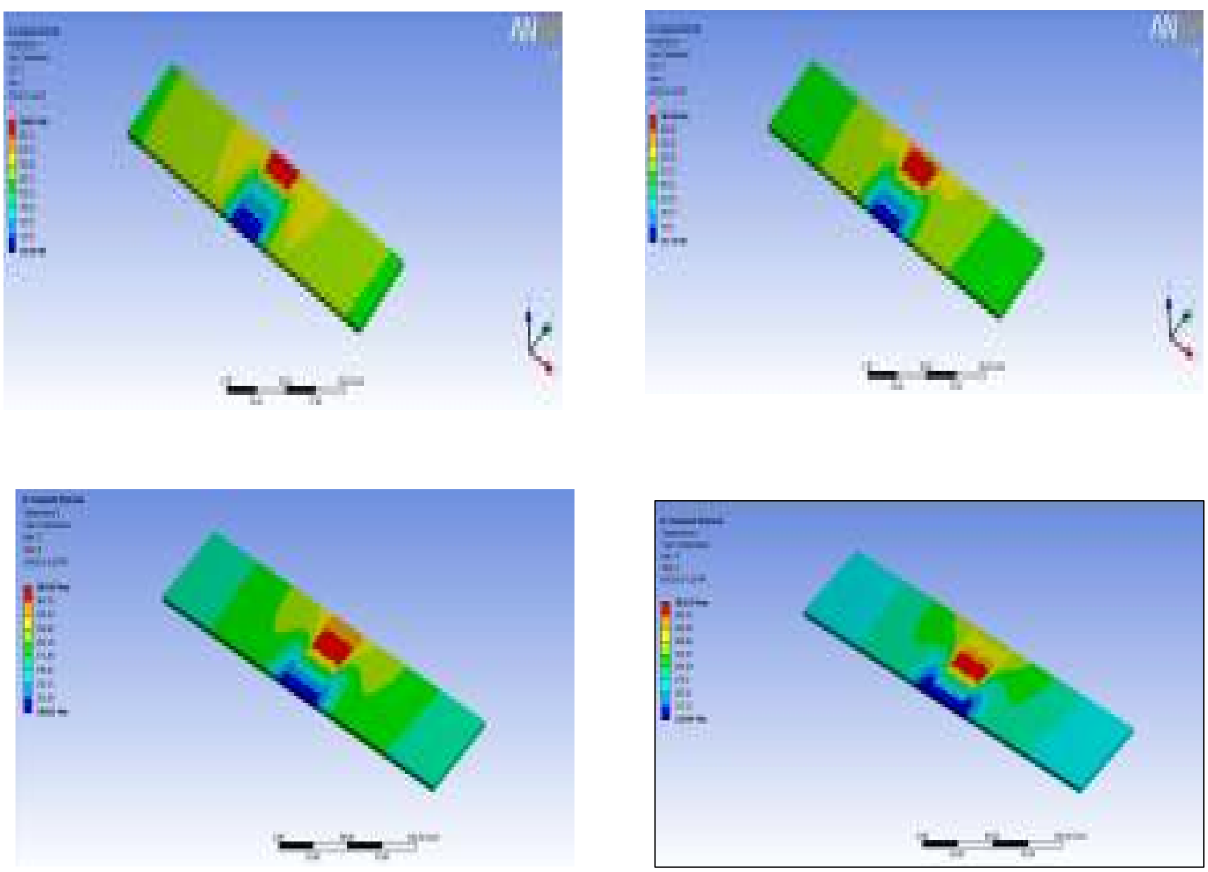
$$k\frac{\partial T}{\partial n}\bigg|_{\Gamma} = h(T - T_0) \quad \text{--(5)}$$

where n is the normal direction vector of boundary T, and h is the convection coefficient. The surface of the work piece in contact with the backup plate is simplified to the convection condition with an effective convection coefficient in this model.

4.3.2. Initial condition: The initial condition for the calculation is:

$$T(x,y,z,0) = T_i \quad \text{---------------------------------(6)}$$

5 Results and discussion: With the above mentioned numerical model, temperature distribution during friction welding is predicted and is illustrated in Figure 4. It shows the thermal distribution at one cross section of the weld reinforcement. The hottest zone of about 380 C exists on the centre of the weld reinforcement. A very high temperature gradient is observed near the weld line. Moreover, higher temperature and heat rate are indicated nearer to the weld line. The temperature gradually decreases with increasing distance from the centre line of the weld reinforcement towards the Heat Affected Zone (HAZ). A cross sectional view of the temperature distribution in the FEM model of friction welding process reveals the bead extent and intensity of heat distribution (figure5).



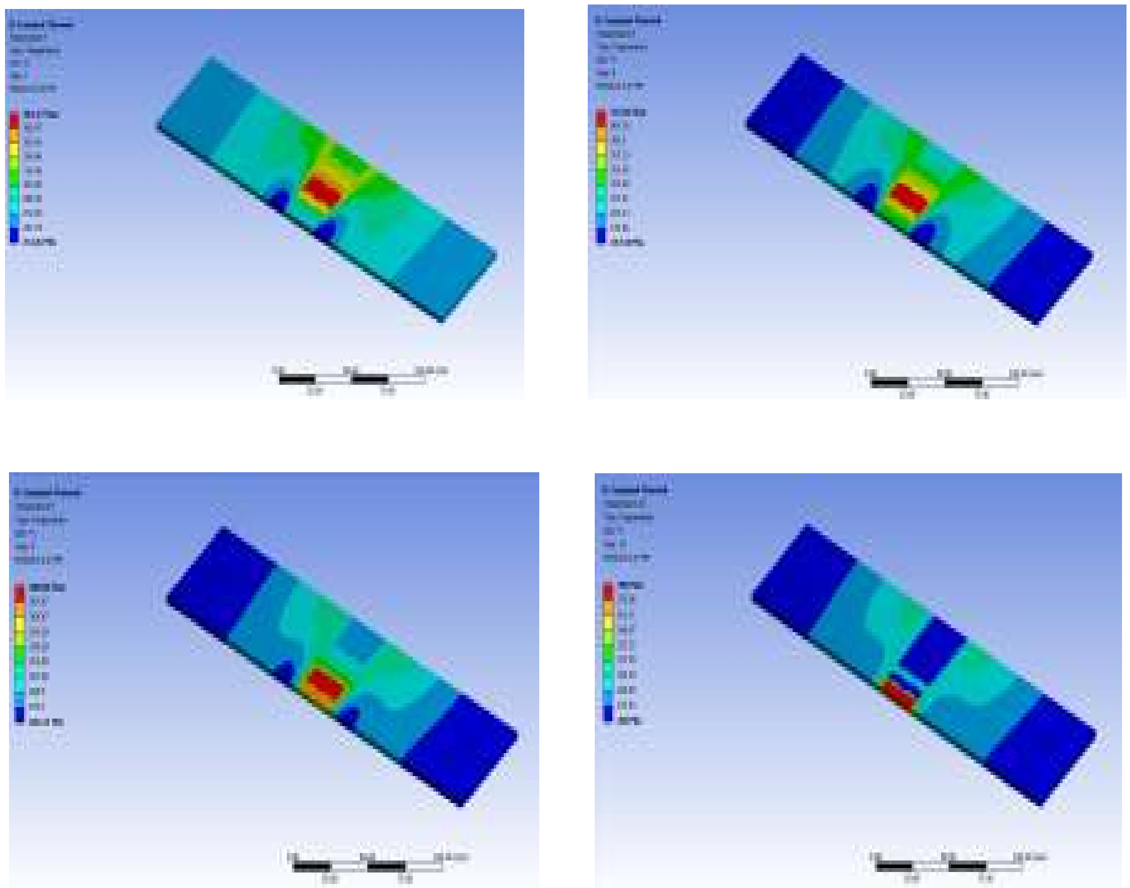


Figure5: Sectional view of the temperature distribution on the weld bead.

5. Validation of the FEM Model:

Measurement of Temperature during Friction Welding Process: The validation of FE model of the friction welding process is carried out by comparing the results of FE model with the experimental results [12] The temperature is measured experimentally for the trial during the friction welding process at the butt ends of the plates to be welded with respect to time (steps of 3 s) using infrared temperature sensor guns and recorded in Table 1. As indicated in Table 1, the peak temperature (just after forging) reaches upto 400C, at the weld joint. However, while recording the temperature using infrared temperature sensor, the sensor is positioned at a slight angle (with respect to the line of weld) and hence is not in exact alignment. Thus, it is expected that the measured temperature (as in Table 1) would be slightly lower than the actual temperature at the center of the reinforcement (approximately 330-430^{o} C). The calculated results of temperature distribution are in good agreement with the experimental results. The numerical calculated results for the shape of the welded joint also show an excellent fit with the experimental observations.

6. Conclusions: Simulations are performed using ANSYS to analyze the distribution of temperature across the weldment along the plates for the friction stir welding process of dissimilar materials

(Composite and steel). The parameters of the system used for the FEA is adopted from the experimental study presented in the literature. Although the proposed model is not an exact or sophisticated model of friction stir welding process, it is adequate to provide an insight into the basic mechanisms of friction stir welding process from the thermal engineering point of view. The results are reasonably good and have a appreciable coherence with the estimated values. Moreover, this study is a pivotal attempt which emphasizes that with proper selection of parameters, FSW is a appropriate option for joining composites and alloys.

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