Heat Transfer Analysis during Friction Stir Welding of Al6061-T6 Alloy

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ABSTRACT
The accurate 3D finite element simulation of the Friction Stir Welding (FSW) process requires a proper knowledge of both material and interface behaviors, but friction, the key phenomenon of this process, is quite difficult to model and identify. Friction stir welding is a relatively new welding process, that has significant advantages compared to the fusion process such as joining conventionally non-fusion weldable alloys. Being a solid-state joining process it produces weld with reduced distortion and improved mechanical properties. The aluminum alloys are widely used in different industrial applications such as ship building, aerospace and automobile industries due to their light weight, good mechanical strength and high corrosion resistance. A three dimensional finite element model is developed to study the thermal history in the butt welding of 6061 aluminum alloy using ANSYS package. Solid 70 elements are used to develop the model. The heat source incorporated in the model involves the friction among the material, probe and shoulder. In this work, a moving co-ordinate has been introduced to model the three-dimensional heat transfer process because it reduces the difficulty of modeling the moving tool. In this model the main parameter considered is the heat input from the tool shoulder and tool pin. The temperature distributions of the weld at various welding speeds are obtained. The friction stir welding experiments are carried out at a transverse speed of 0.75 mm/sec of tool. Brinell's Hardness test, tensile test and micro structure analysis are performed on the welded material.

Keywords **- AAl6061alloys, FSW, Material Flow, *Heat Transfer, FEA.***

I. INTRODUCTION

Friction Stir Welding (FSW) is an efficient solid states joining process that have numerous potential applications in many domains including aerospace, automotive and shipbuilding industries, as well as in the military. It combines frictional heating and stirring motion to soften and mix the interface between the two metal sheets, in order to produce fully consolidated welds. One of its main qualities lies in the possibility of joining materials previously difficult to weld, and to offer excellent mechanical properties.[1].

FSW is based on strong couplings of thermo-mechanical phenomena. It induces very complex material motions and large shear forces. The material temperature is raised to about 80% of the melting temperature [2,3].Never the less the simulation of the process will be a further aim, as it is difficult to be numerically modelled due to the complex thermal and material flux occurring during the process, similar to Friction Stir Welding [4,5].

The conventional processes, working with molten phases are characterized by large heat input, which can change the microstructure of the diverse materials. This can provide mixed phases, which are very brittle and hardly formable, as well as hot cracks due to shrinkage during cooling or shape deviation. Contrary to melting joining techniques Friction Stir Welding is characterized as a solid phase welding technology, which was patented in 1991 [6].The probe primary function is to mix the material under the tool shoulder, which can be enhanced by threads. FSW is actually performed in three steps. First, the probe is plunged into the joint formed by the two sheets to be welded, until the shoulder gets in contact. As the tool rotates at a high velocity, the sheets are heated up by plastic deformation and friction. Second, the tool keeps rotating without any translational motion, so the material heating due to friction increases. Finally, the tool moves along the joint line, heats the material further, moves it from the front of the tool, and deposits it behind its trailing edge, producing the weld. This process is illustrated in Fig. 1.

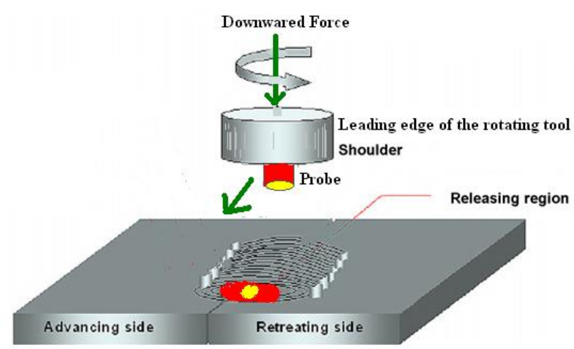


Fig. 1. A schematic representation of the Friction stirs welding process

Thermo-mechanical characterization of aluminium and its alloys has been the subject of various research works produced over a period of time [7-10]. Al–Mg–Si alloys (6xxx series aluminium alloys) present attractive properties with respect to their application in aircraft industries. These properties include medium to high strength, good corrosion resistance, improved weldability performance, good toughness as well as reduced residual stresses in large dimension plates and sheet products. These alloys have been investigated with respect to their mechanical properties, fatigue life, damage tolerance and corrosion resistance in [11,12]. FEA can be used for thermal analyses to evaluate the temperature distribution, and stresses resulting from uneven heating or rapid temperature changes. Thermal analyses may include convection, conduction, radiation, steady-state, and transient analyses. The temperature dependent mechanical properties like the Young's modulus, tensile strength, true stress– strain curves of series 6xxx in T4 and T6 states are also reported in [13-15]. A three- dimensional rigid viscoplasticity model using computational fluid dynamics is carried out, that provides a parametric evaluation of the effect of tool speeds on the temperature field.[16]. The finite difference method and developed a three-dimensional heat flow model, could also calculate the microstructure evolution and hardness distribution in friction stir welds.[17]

II. EXPERIMENTAL ANALYSIS

This experiment deals with a butt weld single pass welded joints of two identical plates made of Al 6061-T6 alloy. The FSW setup consists of 6mm thick plates (yield strength 235MPa), 70mm wide and 220mm long. The plates are jointed such that the distance between the plunging point and the releasing point is 200 mm. The tool is made of HSS tool-steel as shown in Fig.2, having shoulder diameter of 18mm. The pin has a height and diameter of 4.5mm and 8mm respectively.

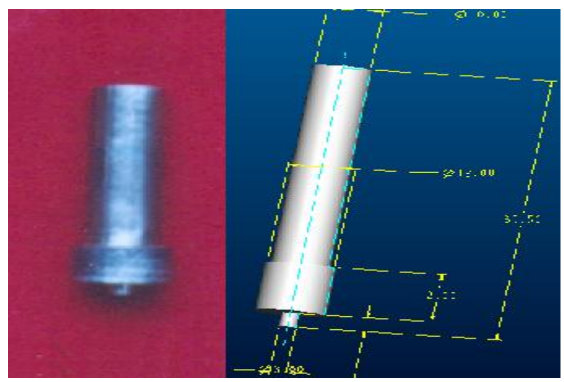


Fig. 2. A photograph view of the Friction stir welding test tool for Experimental and Numerical analysis

FSW is performed at a rotation speed of 1200 rpm, downward force of 23.57MPA and a welding speed of 0.75 mm/sec tool-to-work piece angle was maintained at approximately 2.5◦ and an effective plunge depth of 6mm. At these values of the welding parameters, an adequate welding quality was obtained and the heat distributions were measured in the friction stir weldment of Al6061-T6 plate.

Table1.Nominal chemical composition of Al6061 alloy

Base material	Yield strength (Mpa)	Ultimate tensile strength (Mpa)	Brinel hardness (BHN)	Elongation (%)
AA6061-T6	235	283	105	26.4

The base material used in this investigation is 6061-T6 grade aluminum alloy. Rolled plates of 6 mm of thickness have been used as the base material for preparing single pass welded joints. The chemical composition and mechanical properties of base metal are presented in table 1 and table 2 respectively. The initial joints configuration was obtained by securing the plates in position using proper clamps and fixtures.

Table 2. Mechanical Properties of Base metal

Elements	Percentage
Si	0.43
Fe	0.43
Cu	0.24
Mn	0.139
Ni	<0.05
Pb	0.024
Zn	0.006
Ti	0.022
Sn	0.001
Mg	0.802
Cr	0.184
Al	Balance

The Temperature values in the test are measured at the mid-plane of the plates with thermocouples inserted in small holes drilled in the plates as shown in Fig.3. The holes are aligned along a line normal to the welding direction. Temperature history values at various distances away from the weld line are then measured. Based on the measured values and steady-state condition, temperature variations along lines passing the measurement points and parallel to the weld line can be derived.

Fig. 3. A photograph view of the Friction stir welding test arrangement for temperature measurement

III. NUMERICAL ANALYSIS

The commercial finite element package ANSYS is used as the solver in the current research. The geometry and the boundary conditions of the developed model of FSW are shown in Fig. 4.The SOLID70 element were used, it is eight nodes with a single degree of freedom. Orthotropic material properties is applicable to a 3D analysis, steady-state or transient thermal analysis. The element also can compensate for mass transport heat flow from a constant velocity field. The dimension of the plate, tool and working parameters are same in both the experimental and Numerical analysis.

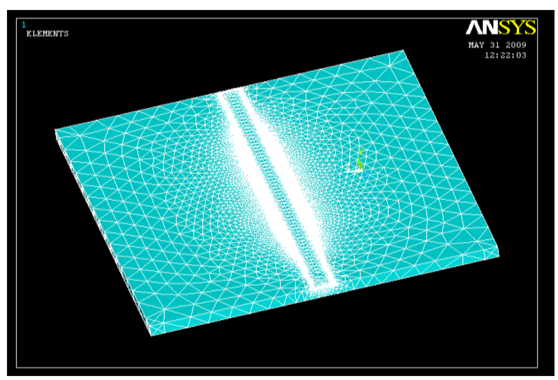
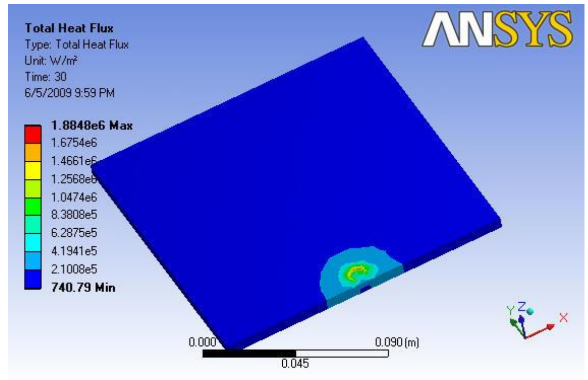


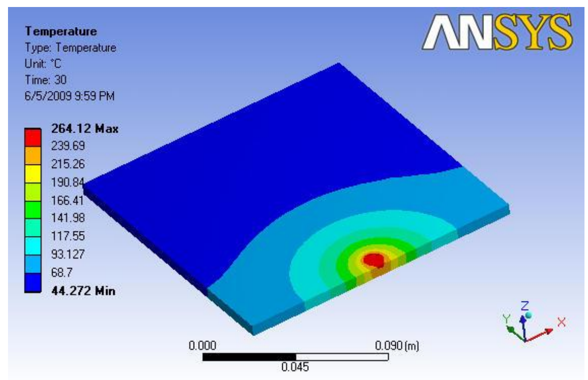
Fig. 4. A view of Finite Element mesh of Friction stir welding plate

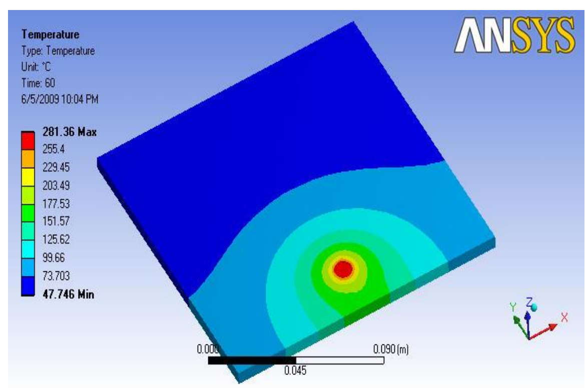
An advancing side and a Retreating side can be defined. Joining of the plates is achieved through the combined action of friction heating generated at the shoulder-plate interface and the forging effect created by the movement of the pin between two tightly held plates. As a first-order approximation, and to work within the bounds of current computational constraints, the FSW process is modeled as a three-dimensional problem. It is assumed that the plates to be joined are thick enough such that a state of plane strain can be achieved in the mid-plane. Because the tool is made of a material much stiffer than the plate material, the tool pin is taken to be rigid. Even though a fully coupled thermomechanical simulation procedure has been devised using a general- purpose commercial finite element code, in which deformation and material flow field, as well as the temperature field, can be computed simultaneously, the limitation of our current PC-based computing power makes such a procedure impractical at this time. As such, the simulation procedure employed in this study is focused on determining the deformation and material flow fields. To compensate for the lack of a predicted temperature field, measured temperature values from an actual FSW test [18] are used to construct an approximate temperature field for the FSW process. This temperature field is then used as input for the solid mechanics model for the same FSW process. As such, a problem geometry that accommodates the simulation of the preceding FSW test is used.

IV. RESULTS AND DISCUSSION

The test was conducted Numerical and Experimental analysis on the Al6061-T6 alloy with the dimension of 300 x 75 x 6 mm by using ANSYS (Numerical Analysis) and FSW machine (Experimental analysis) with transverse speed of 0.75 mm/s, download force of 23.57 MPa and rotational speed of 1200rpm.The Numerical temperature distribution of the plate is shown in Fig.5 and also the Experimental temperature distribution of the plate is calculated by using thermocouple, the time Vs temperature curves were plotted is shown in Fig.6. From the graph, temperature ranges are high of order from 300 C to 550 C towards the tool and low temperature ranges from 30 C to 35 C away from the tool during welding process. The prediction and the measurement show that the maximum temperature gradients in longitudinal and lateral directions are located just beyond the shoulder edge.







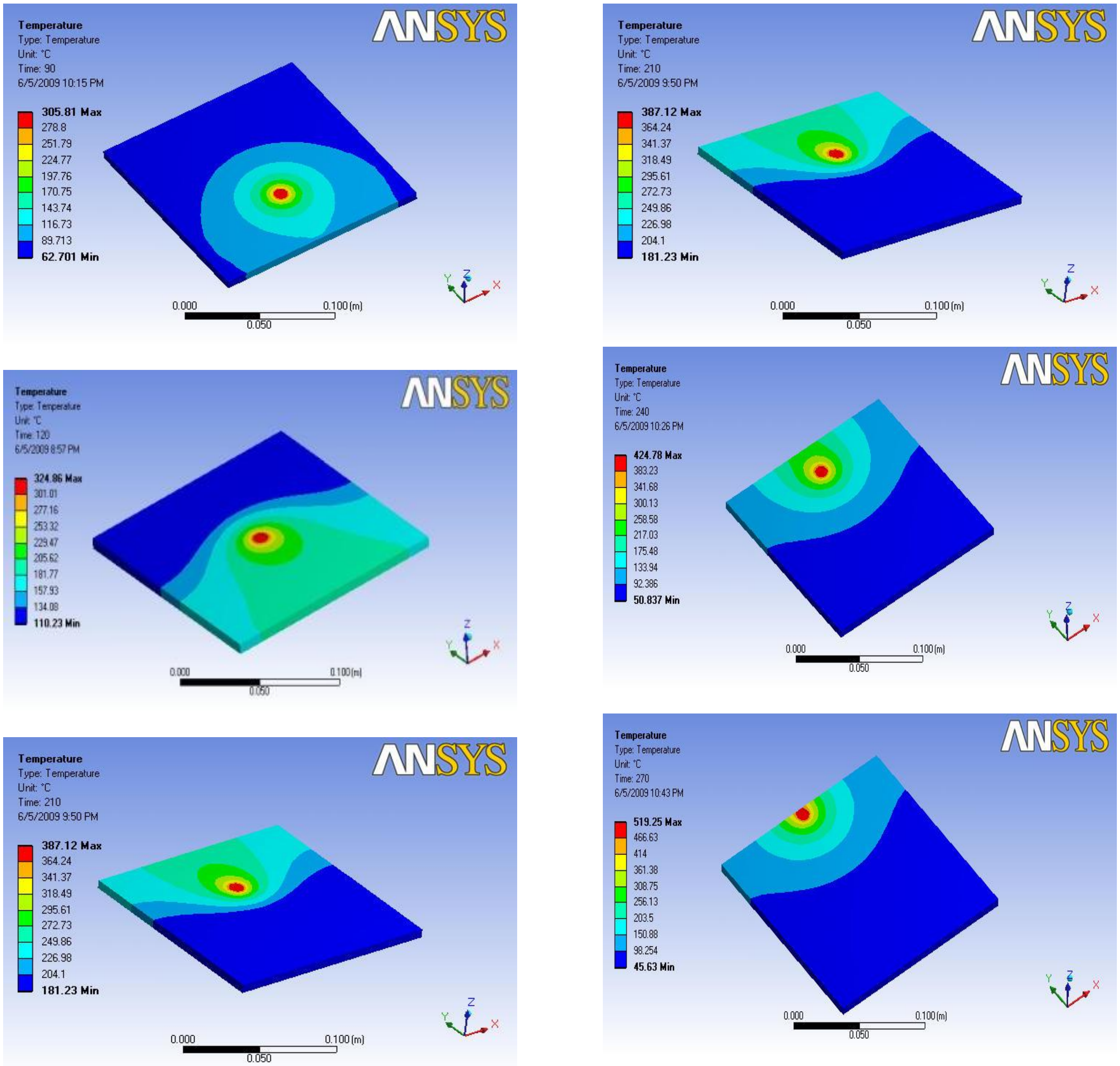
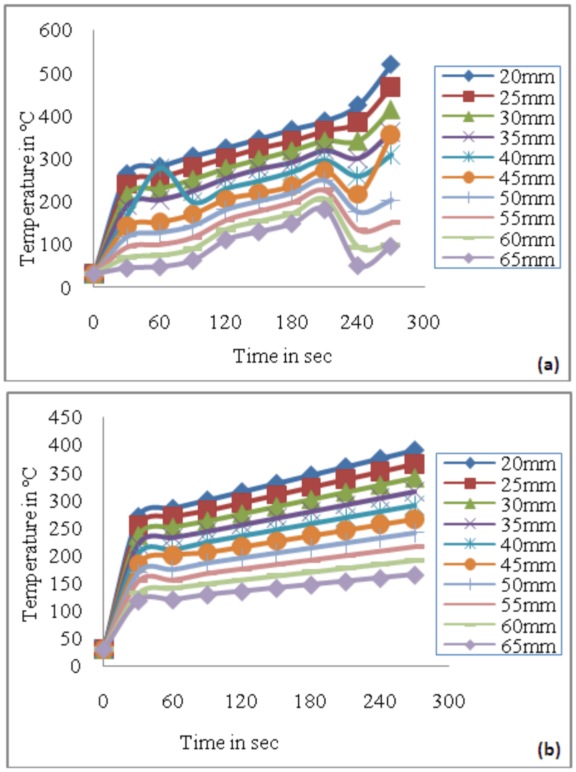


Fig.5. A View of temperature maps of the Al606-T6 alloy of 30s, 60s, 90s, 120s, 150s, 180s, 210s, and 240s of welding (steady state conditions) using the ANSYS model with af=0.4 and q=0.1

From the analysis results, the temperature values are increased with respect to increase in time duration, along with the weld axis. From the experiment results, the temperature values are decreased with respect to increase in distance and increased with respect to time duration along with perpendicular to the weld axis.



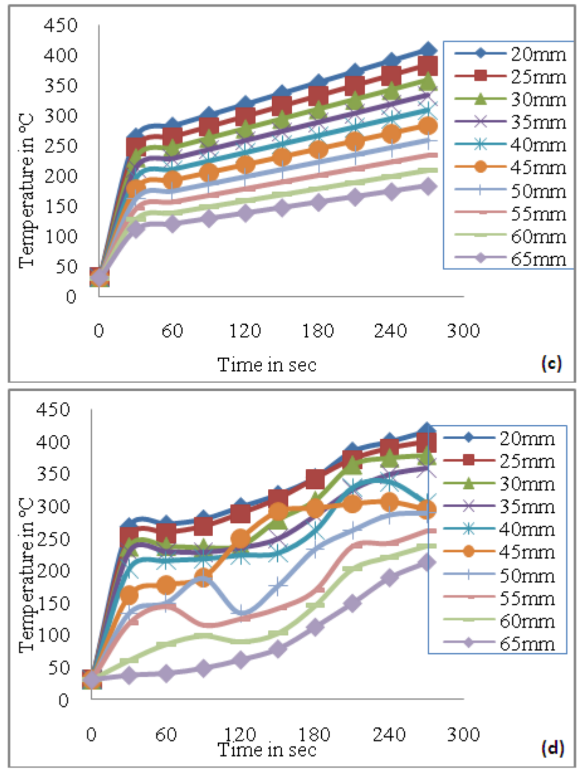


Fig.6 Stir welding temperature as a function of welding time at varies distance weld area of (a)Advanced side(Experimental), (b) Retreating side(Experimental), (c)Advanced side(Numerical) and (d) Retreating side(Numerical)

From the mechanical properties testing, it is observed from the results tabulation that the mechanical properties like yield strength, ultimate strength, hardness and elongation are more reliable in the retreating side than the advancing side. From the experimental and as well as analysis it is clearly observed in FSW weldment retreating side temperature distribution is relatively higher than the advancing side is shown in Fig.7.

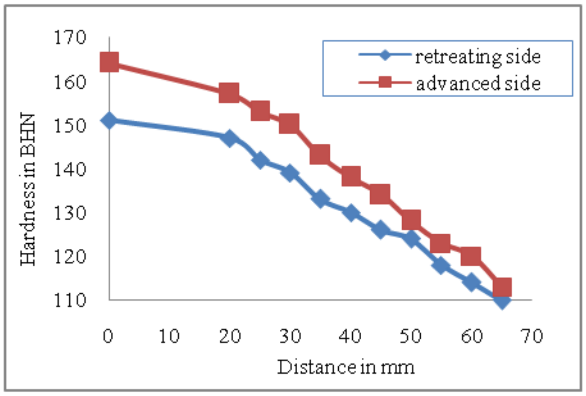


Fig.7. Hardness of Al6061-T6 alloy from weld area

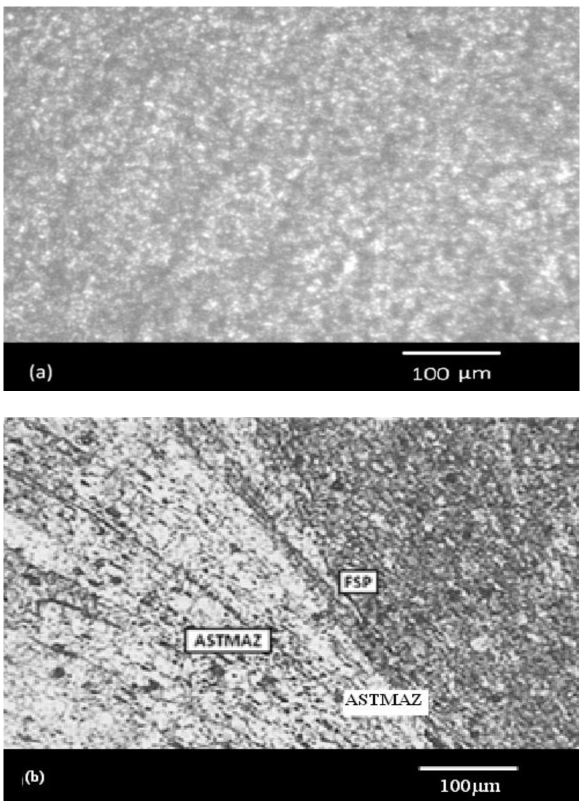


Fig. 8. Optical Micrograph of Al6061-T6 Alloy and Welded area

A microstructure analysis indicates that change in grain morphology is more obvious for Weld area than for AA6061 alloy is shown in Fig.8. Equiaxed and more homogeneous grains are seen in these specimens due to absence of HAZ (heat affected zone). Grain growth in the bonded materials can be attributed to recrystalliation and to the enveloping of small grains by bigger ones. The tendency for grain growth after recrystallization is related to temperature distribution. In order to obtain a lower level of temperature, total grain boundary per unit volume needs decreasing and this, in turn, requires the growth of grains. However, it is well known that grain growth is not desirable

V. CONCLUSION

The analytical model used for the temperature analysis has been demonstrated for a particular tool geometry and material property. Based on this study following conclusions can be drawn.

[1] The mechanical properties are tested for transverse speed of 0.75 mm/sec, by keeping spindle speed and downward force as constant. From this test, the yield strength, ultimate strength, elongation and hardness are more reliable in the retreating side than the advancing side.

[2] From the experimental and Numerical analysis, it is clearly observed in FSW weldment retreating side temperature distribution is relatively higher than the advancing side

[3] The analytical heat input model has been used for the determination of thermal history and based on which finite element analysis has been carried out and the predicted values were confirmed with experimental measurement data.

[4] The asymmetry in the residual stress distribution is due to the asymmetry in the plasticized material volume along the advancing and retreating side of the stir zone that generated the heat.

[5] A three-dimensional thermo mechanical model and the thermo mechanical effect of the welded material is developed for the FSW of an Al-alloy, in order to build qualitative framework to understand the thermo mechanical process in FSW.

[6] Modeling and measurement of Al6061 alloy is conducted and the experimental values validate the efficiency of the proposed model.

[7] The microstructure of the friction stir welded Al6061 alloy joints and the observations made from the microstructure are presented in the figures, found to be free from defects.

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