Thermomechanical Modeling and Experimental Evaluation to Study Peak Temperature and Flow Stress of Friction Stir Welds of Aluminum Alloy 6061

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***Abstract*— This work involves three-dimensional thermomechanical modeling of Friction Stir Welding (FSW) process using general purpose Finite Element Analysis (FEA) simulation tool 'Altair Hyperworks' from the combined complementary effort of experimental evaluation and numerical modeling to understand FSW process. Thermal and mechanical behavior of the material which are mutually dependent are coupled together to simulate the FSW process model similar to the real time to evaluate the peak temperature and flow stress. The heat generation is governed by friction between tool and workpiece, plastic deformation and the temperature imposed subsequently on the material. The temperature distribution in the workpiece during FSW process of butt joining of aluminum alloy 6061-T6 is experimentally measured from the devised thermocouple layout at different locations on the workpiece in the welding direction. The temperature history and normal force predicted from simulated model is compared with that of experimental values and is found to be in good agreement validating the numerical model. Parametric study to determine the effects of tool rotational and traverse speed on the performance of weld is carried out by predicting peak temperatures, flow stress, strain rate and normal force. The peak temperature during welding is found to be increase as tool rotation speed is increased at constant traverse speed leading to formation of defects due to lower flow stress and high strain rate. On the other hand as the tool traverse rate is increased the total heat input decreased which decreases weld temperature at constant rotational speed increasing the flow stress leading to formation of defects. This provides better insight about the peak temperature, flow stress and strain rate developed at different tool speeds by numerical modeling without conducting costlier experiments. The results predicted from the numerical modeling leads to the better understanding of effect of flow stress and strain rate on normal force which can be measured during FSW to aid the assessment of weld performance.**

Keywords— ***Friction stir welding, Finite element analysis, Thermomechanical modeling, Temperature history, Flow stress.***

I. INTRODUCTION

FSW is a new solid state joining process derived from conventional friction welding without melting of material, which enables high quality weld being fabricated with absence of solidification cracking, porosity, oxidation and other defects which typical appear in traditional fusion welding. FSW technique is viable for joining aluminum alloys, copper, magnesium and other low-melting point metallic materials. Its potential to join harder materials such as steel and titanium is also being explored. The basic concept of FSW involves inserting the pin of rotating non consumable tool whose height is just shorter than the plate thickness into the joint interface of plates to be welded. The tool shoulder plunged to make contact with the workpiece surface, generates heat due to friction. The heat developed plasticizes the material below the melting point allowing the tool to traverse along the weld line, transferring the material from the leading edge of the tool to the trailing edge where it cools and consolidates to produce a weld in the solid phase [1].

The FSW process involves relatively high temperatures and very high strain rates. The alternation in physical and mechanical properties of the weld during interactions between different process parameters and their distribution is difficult to understand. Computer simulation of FSW numerical model is good at examining these interactions and allows analyzing the influence of different weld parameters without performing costly experiments. The evaluation of the temperature field is very important to know the time–temperature history of the welds which promote phase transformations. Usually, FSW temperature is measured using thermocouples. However, the process of measuring temperature variations in the nugget zone using the above technique is a very difficult task. In the last few years numerical models are developed efficiently and been used conveniently to predict thermal history of FSW. Therefore, in order to attain the best weld properties, numerical simulations can help to adjust and optimize the process parameters and tool design.

Diogo Mariano Neto et al. [2] presents a literature review on friction stir welding (FSW) modeling with a special focus on the heat generation due to the contact conditions between the FSW tool and the workpiece. The contact conditions (sliding/sticking) as well as an analytical model that allows estimating the associated heat generation are presented. Different approaches that have been used to investigate the material flow are presented and their advantages/drawbacks are discussed. A reliable FSW process modeling found to depend on the fine tuning of some process and material parameters, which are usually achieved with base on experimental data. The numerical modeling of the

FSW process can help to achieve such parameters with less effort and with economic advantages. Since, FSW modeling helps to visualize the behavior of the welded materials and allows to analyze the influence of different weld parameters and boundary conditions, without performing costly experiments.

Ulysee [3] presented three-dimensional visco-plastic modeling of FSW of butt joints of thick aluminum plates to improve the understanding of process by assessing the model capabilities. Parametrically studied the effect of tool speeds on welding temperatures and forces acting on the pin and found that increasing welding speed has the effect of increasing the magnitude of forces, while increasing the rotational speed has the opposite effect. The predicted forces on the pin may used to avoid tool fracture during welding. Chen and Kovacevic [4] used a commercial FEA package, ANSYS to perform 3-D modeling of FSW for studying the mechanical effect of the tool by evaluating thermal history and stresses in the weld. Parametrically studied the effects of varying the traverse speed of the tool and found that the maximum temperature gradients are located just beyond the shoulder edge. Zhu and Chao [5] presented 3-D nonlinear thermal and thermomechanical simulations using FEA code – WELDSIM on 304L stainless steel friction stir welded plates. Estimates heat input and heat transfer coefficient by fitting the measured temperature data with the analytical model. Later, the transient temperature outputs from the first stage were used to determine residual stresses in the welded plates using a 3-D elastic plastic thermomechanical model. Convection and radiation were assumed to be responsible for heat loss to the ambient on the surface. Their model provided good match between experimental and predicted results.

The FSW model proposed by Buffa et al.[6] using DEFORM-3DTM, a Lagrangian implicit code. A rigid-viscoplastic material model was employed and material constants were determined by numerical regression based on experimental data. They assumed heat generation was due only to plastic and frictional conditions at the tool-workpiece interface. The model was able to predict the temperature, strain, strain rate as well as material flow and forces. Good agreement was obtained when comparing the results of the simulation with experimental data. Khandkar M.Z.H et al.[7,8] presented three-dimensional torque based model of FSW process to predict the temperature distribution and residual stress during FSW. In this study combined modeling and experimental approach has been used to determine the distribution of temperature and stresses. Reasonable agreement between simulated temperature profiles and experimental data has been observed. Robert Hamilton et al.[9] proposed multiphysics model simulating the plunge, dwell and traverse stages of the friction stir welding process. The field variables: temperature, stress and plastic strain are quantified by the model. The predicted maximum temperature is higher than material melting point, resulting in a lower stress field than expected around the tool during welding. Material movement is visualized by defining tracer particles at the locations of interest. The numerically computed material flow patterns are in very good agreement with the general findings in experiments.

In this paper, a three-dimensional model of FSW using general purpose FEA simulation tool 'Altair Hyperworks' is modeled to evaluate the thermal history and temperature dependent flow stress and strain rate to understand the performance of weld. Experimental trails by welding butt joints of AA6061-T6 alloy is conducted to measure temperature history using thermocouple device and normal force during welding for the comparison with the simulated results for validating the numerical model. Parametric study is carried out to study the effects of tool rotational and traverse speed on weld performance by predicting thermal history, strain rate and flow stress.

II. MODEL DESCRIPTION

The FSW process shown in Fig.1, where tool rotates with speed ω and traverse at speed V. The tool is considered to be rigid made of H_13 tool steel with a pin and flat shoulder of configuration listed in Table 1. The welded plates are considered ductile with elasticity, plasticity made of AA6061-T6 of rectangular shape of dimensions 300mm x 75mm x 5mm. The process parameters considered includes: workpiece temperature, tool translation speed, tool rotational speed, coefficient of friction between tool and workpiece. The coefficient friction is estimated considering a purely rotating tool shoulder (neglecting the translation velocity) by analogy with conventional rotary friction welding, for a slipping contact [4], the rate of heat generation caused by friction over the entire interface of the contact q is given by:

$$q = \frac{2\pi}{3}\mu\, p\, \omega\, R_s^3 = \mu\, F\, R_s \omega = \mu T \omega$$

Where,
μ is the coefficient of friction,
p is the normal pressure,
ω is the angular velocity (radians/s),
R_s is the tool shoulder radius (neglecting the central area occupied by the probe).
T is the torque and
F is the normal force
Modern FSW equipment routinely outputs torque T, so that total heat input from the machine may be directly found from the product $T\omega$, from which coefficient of friction can be estimated. The process parameters used and coefficient of friction estimated using above relation is listed in Table 2.

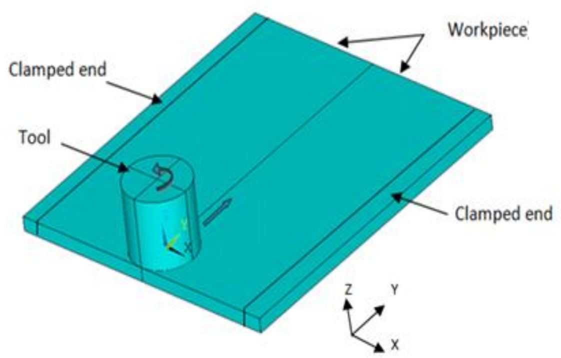

Fig.1 Schematic diagram of FSW process [13]

TABLE 1. TOOL CONFIGURATION

Pin length	4.80mm
Pin Diameter	4.5mm
Shoulder Diameter	20mm
Shoulder Length	70mm
Tool tilt	2^0

TABLE 2. PROCESS PARAMETERS AND COEFFICIENT OF FRICTION

Weld No.	Tool rotation speed (rpm)	Tool traverse rate (mm/min)	Coefficient of friction (μ)
1	700	63	0.44
2	1000	63	0.40
3	800	150	0.42

TABLE 3.PROPERTIES OF TOOL AND WORKPIECE MATERIAL

Material		Density (g/cm^3)	Melting point (^{0}C)	Modulus of Elasticity (GPa)	Poisson ratio	Ultimate Tensile Strength (MPa)	Shear Modulus (GPa)	Specific Heat J/kg ^{0}C	Thermal Conductivity W/m^{0}C
Tool	AISI Type H13 Tool Steel	7.8	-	210	0.3	1990	81.0	485	22
Work piece	AA6061-T6	2.7	580	70.0	0.35	310	26.0	945	162

In order to accurately predict the temperature fields and flow stress, reliable tool and workpiece material properties that relate to both heat transfer and deformation need to be input. The material properties commonly used for heat transfer modeling are the thermal conductivity, heat capacity and emissivity of the workpiece and tool materials. These properties are usually defined as a function of temperature. The flow stress of the workpiece material is very important for the correct prediction of metal flow behavior. It is usually defined as a function of strain rate and temperature. The Young's modulus, the Poisson's ratio as a function of temperature, and the thermal expansion coefficients of the work and tool materials are important parameters for simulating the FSW process. The temperature dependent properties are listed in Table 3 above.

A. Thermal Model

The tool shoulder provides heating and constrains the deformation zone, while the probe, shapes the deformation path that seals the joint and also generates a proportion of the heat, depending on the tool dimensions. The tool rotates at high speeds, such that the peripheral speed of the shoulder and probe is very much greater than the translational speed. FSW primarily uses viscous dissipation in the workpiece material, driven by high shear stresses at the tool/ workpiece interface.

The frictional and plastic heat generated during the FSW process propagates rapidly into remote regions of the plates. On the top and side surfaces of the workpiece, convection and radiation account for heat loss to the ambient. Conduction losses also occur from the bottom surface of the workpiece to the backing plate. Thermal boundary conditions applied is shown in Fig.2.

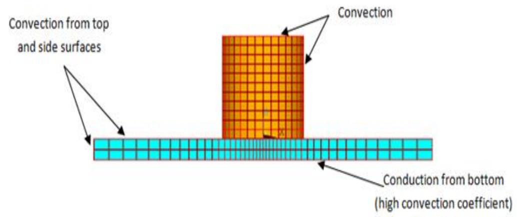

Fig.2 Thermal Boundary Conditions [13]

The value of the convection coefficient is 250 W/m^2 ^{0}C for workpiece and 200 W/m^2 ^{0}C for tool is considered which affects the output temperature. A lower coefficient increases the output temperature of the model. A high overall heat-transfer coefficient of 250 W/m^2 ^{0}C is assumed for the conductive heat loss through the bottom surface of the workpiece. As a result, the bottom surface of the workpiece is also treated as a convection surface for modeling conduction losses. Since the percentage of heat lost due to radiation is low, radiation heat losses are ignored. An initial temperature of 28^{0}C is applied on the model. Temperature boundary conditions are not imposed anywhere on the model.

B. Mechanical Model

The workpiece is fixed by clamping each plate along the length at outer edge. The clamped portions of the plates are constrained in all directions. To simulate support at the bottom of the plates, all bottom nodes of the workpiece are constrained in the perpendicular direction (z direction).

C. Finite Element Model

FEA simulation software "Altair Hyperworks" is used for three dimensional thermomechanical modeling of butt joining of aluminum plates and solved using "HyperXtrude" solver. Hex20 elements which is 3D (2nd order) hexahedra elements with 20 nodes which supports nonlinear direct coupled field analysis with both thermal and structural degrees of freedom is used for mesh generation. In FSW process the thermal and mechanical behavior are mutually dependent on each other. The heat is generated due to friction and plastic deformation at the tool workpiece interface. The resulting temperature field affects the metal flow and stress distribution during welding, which also determines the microstructure and mechanical properties at the weld nugget, thermomechanically affected zone and at heat affected zone of the work material. The accurate values of temperature fields, strain rate, flow stress and normal tool force during the joint formation are predicted for varying range of process parameters.

III. EXPERIMENT SET UP

K-type thermocouples are used to measure the temperature during FSW. USB-TC controller, a USB-based 8-channel thermocouple input device is used for acquisition of temperature data during FSW. The holes of 0.8mm diameter and 3mm depth were drilled on workpiece to accommodate the thermocouples. The thermocouple layout is devised along the weld direction to measure the temperature histories as shown in Fig.3. The FSW was carried out on ETA stir welding machine which is fully automated with computerized facilities to record forces and torque applied during welding. The three butt joints with different weld parameters (Table 2) are welded. The normal force developed during welding are recorded (Fig.4), which shows variations during the 3 stages of FSW; plunging, dwell period and tool traverse along weld line. The temperature history at different time intervals are measured during FSW by thermocouples.

IV. RESULTS AND DISCUSSION

A. *Numerical Model Validation*

In order to simulate FSW process similar to real time welding and to predict output results accurately, the model developed using FEA is validated by comparing the temperature history and normal force measured during FSW with that of predicted values. In the experiments, six thermocouples were inserted along the line located at 25mm from the weld line. The typical thermal history measured during weld 1 (700rpm, 63mm/min) by thermocouple 0, 1 and 5 is shown in Fig.5. The variations in the temperatures recorded by the thermocouples are seen, which may be due to difference in contact of the thermocouples with workpiece. The thermocouple data measured by channel 1 shows well distributed and maximum temperature which will be used for validation [3]. The temperature distribution in the workpiece predicted by FEA model is compared with experimental values (Fig.6). The temperature predicted by FEA tends to little higher compared to experimental values. It may be due to assumption of a constant temperature of backing plate. The average normal force during steady state of FSW is compared with that of predicated values obtained by integrating the stress (Fig.7). Reasonably good agreement between experimental results and FEA results are found validating the numerical model.

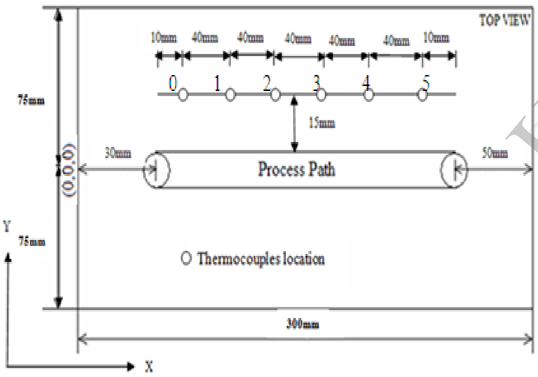

Fig.3 Thermocouple layout

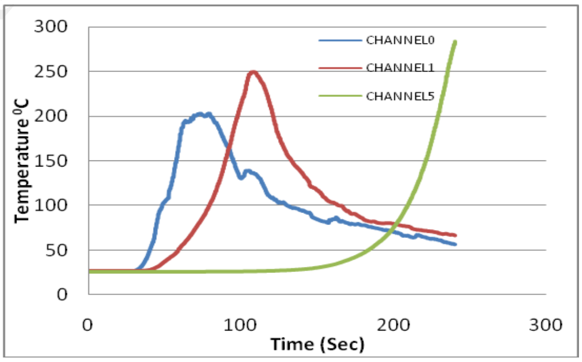

Fig.5 Temperature data recorded during FSW of weld1

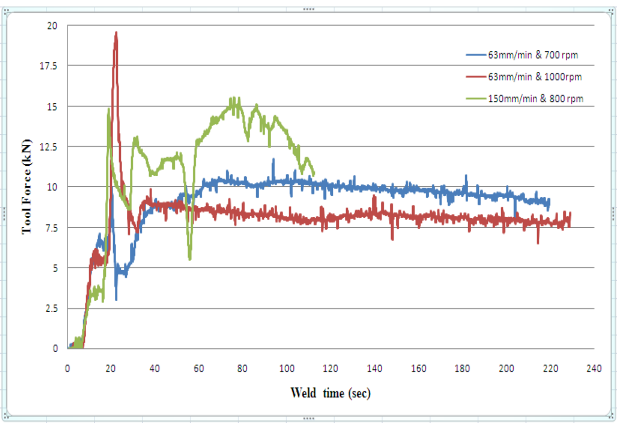

Fig.4 Normal Force exerted by tool during welding

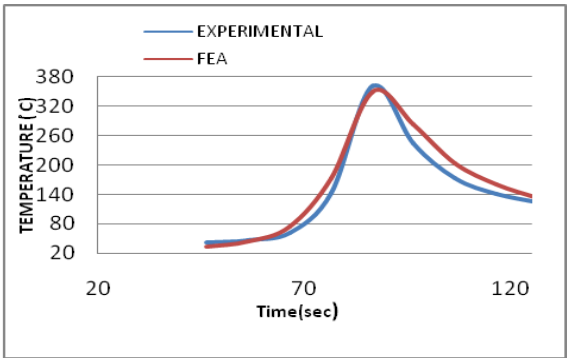

Fig.6 Comparison of temperature history at the location of thermocouple 1

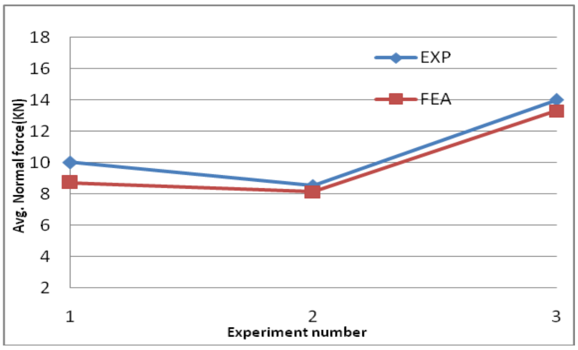

Fig.7 Comparison of average normal force of weld 1, 2 and 3

B. *Numerical Results*

The contours of temperature field, flow stress and strain rate predicted during simulation of three-dimensional thermomechanical model of FSW of AA6061-T6 are plotted typically for weld 1(700rpm, 63mm/min). The temperature distribution on top surface of the workpiece (Fig.8) shows conduction of heat generated at the interface to the workpiece ahead of the tool. The temperature distribution near the tool pin where the maximum plastic deformation is taking place is shown in Fig.9.The temperature here is about 468.741^{0} C which is well below the melting point temperature of the workpiece. Fig.10 shows the distribution of flow stress on top surface of the workpiece during FSW. The flow stress in the area close to the tool is found to be very less (about 80MPa), which is due to very high temperatures in this region. The maximum plastic deformation takes place near the tool pin. Hence, high strain rates in the region close to the pin during FSW is observed (Fig.11).

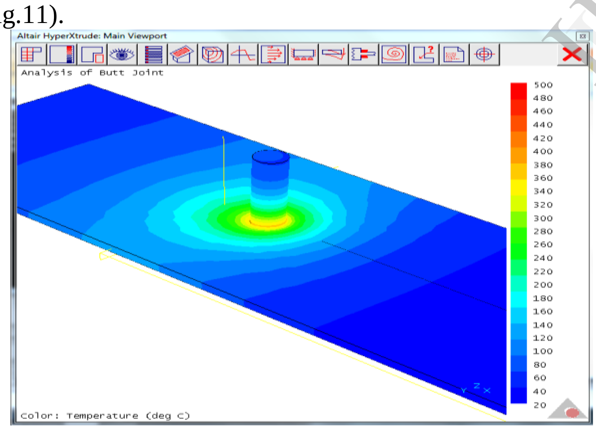

Fig.8 Temperature contours along FSW surface of model 1

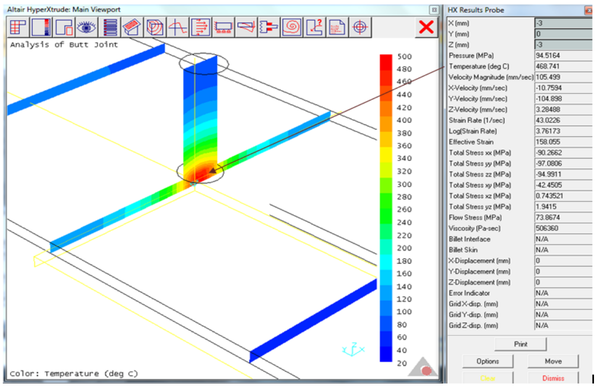

Fig.9 Temperature distribution near the tool pin of model1

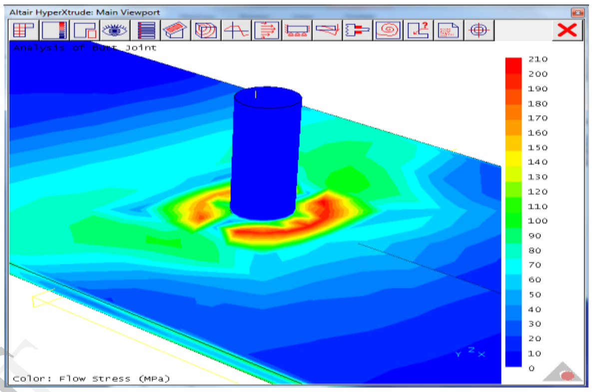

Fig.10 Flow stress contours along FSW Surface of model 1

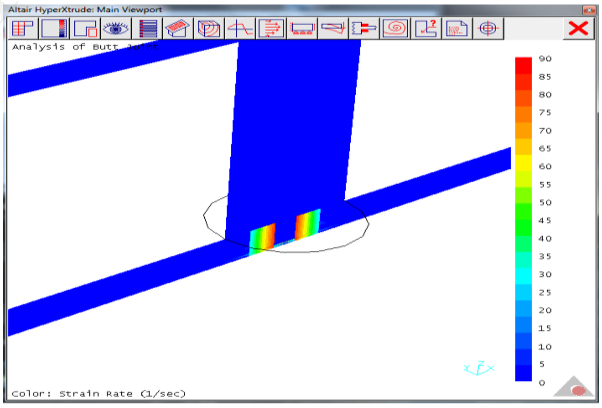

Fig.11 Strain rate distribution near the tool pin of model 1

The variations in the temperature, strain rate and flow stress predicted during simulation of FSW of model 1, 2, and 3 for different tool rotational and traverse speeds is shown in Fig.12. The temperature predicted during FSW (Fig.12a) is found to increase as the tool starts traversing along the weld line and attains steady state due to the cumulative heat added to the work material by the tool action during welding. Significant plastic flow occurs in close proximity of the tool and the temperatures are high in this region leading to low flow stress (Fig.12b) which is essential for material flow by continuous plastic deformation of work material around the tool pin and under the shoulder increasing the strain rate (Fig.12c). The variations in the peak temperature and strain rate leads to variations in flow stress. The more insight on the effect of tool rotational and traverse speed on performance of

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weld is obtained by conducting the parametric study. The reaction force which is acting normal to the tool traverse direction during weld formation is determined from the stress. It depends upon the temperature and flow stress developed during welding beneath the shoulder surface. It is an important parameter which can be measured during FSW process to aid the assessment of weld performance.

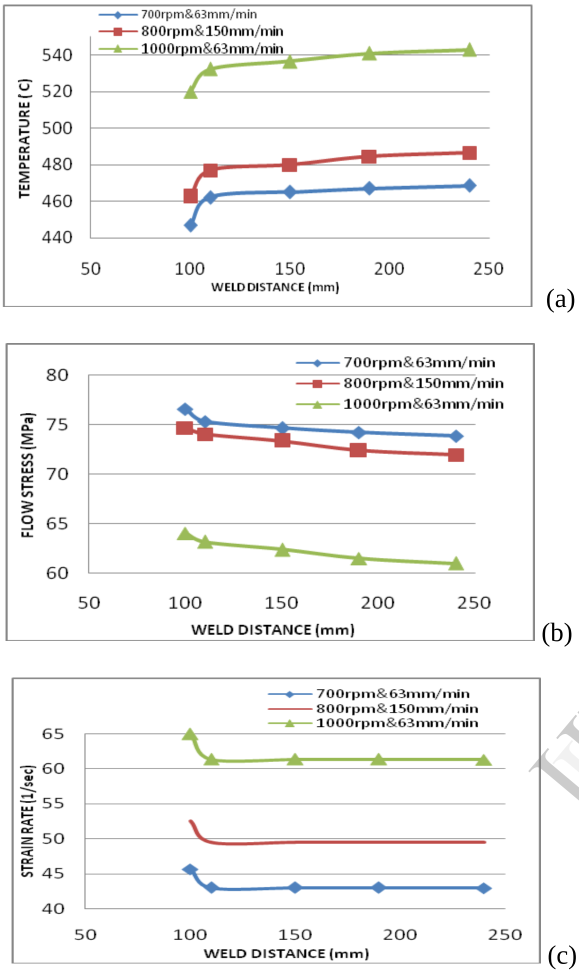


Fig.12 Predicted results for FSW model 1, 2 and 3: (a) Temperature, (b) Flow stress and (c) Strain rate

A study of the effect of tool rotational speed on weld quality is carried out by predicting the peak temperatures, strain rate, flow stress and normal reaction force developed at different tool rotation speeds at constant tool traverse rate (Table 4). It is observed that peak temperatures during welding is increased when the tool rotation speed increases (Fig.13a), which leads to increase in strain rate (Fig.13b) decreasing the flow stresses (Fig.13c) and the normal force (Fig.13d) reducing the quality of weld. This can be explained by the following two reasons: Firstly, the co-efficient of friction decreases when a local melt occurs, and subsequently decreases when a local input increases; secondly, the latent heat absorbs some heat input. Thus, increase in rotational speed increases heat input within the stirred zone due to the higher frictional heat. Which causes intense stirring and mixing of materials releasing excessive stirred material to the upper surface in the form of flash, producing micro voids in the stir zone [11].

The predicted peak temperatures, flow stress, strain rate and average normal reaction force developed at different tool Traverse speed for given tool rotational speeds is listed in Table 5. At constant tool rotational speed, it is observed that
peak temperatures during welding decreases when the tool

traverse speed increases (Fig.14a),which leads to increase in flow stresses (Fig.14b) and the normal force (Fig.14d) reducing the quality of weld. The strain rate (Fig.14c) is observed to be almost constant. This is because; the traverse speed governs how much time the tool spends in contact with a given area of the workpiece. A fast moving tool will spend less time over an area and so will heat it less than a slow moving tool. If the tool speed is high the material ahead of the tool will be too cold and the flow stress increases to permit adequate material movement which causes lack of bonding and leads to the formation of defects or tool fracture [11].

In FSW material flow in the top portion of the weld nugget during tool traverse reaches the advancing side of base material and makes the solid-state bonding producing the joint. It essentially requires adequate hydrostatic pressure and temperature (below melting point) generated in the weld region to form defect free weld. The temperature and hydrostatic pressure generated during friction stir welding defines the amount of plasticized metal which greatly dependent on the axial tool force [11-12]. From the above parametric studies it is evident that as tool rotation speed increases, the peak temperature developed during welding

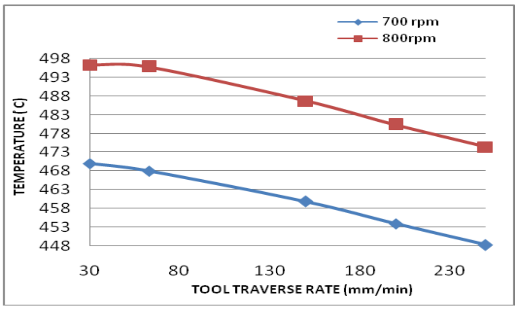
Table.4 Predicted results at constant tool traverse rate and varying tool rotation speed

Sl No.	Tool Traverse Rate (mm/min)	Tool Rotation (rpm)	Peak temperature (^{0}c)	Flow stress (MPa)	Strain rate (1/sec)	Normal Force (kN)
1	63	500	404	87.6	30.79	12.2
2		700	468.7	73.87	43	10.0
3		1000	543	61	61.3	8.5
4		1300	602	52	78	7.3
5		1500	638	48	91	6.7
6	150	500	396.831	91.5745	31.125	13.0
7		700	459.889	77.206	43.3839	10.75
8		1000	533.553	63.7972	61.7602	9.0
9		1300	592.185	55.0999	80.127	7.7
10		1500	626.338	50.5822	92.3668	7.0

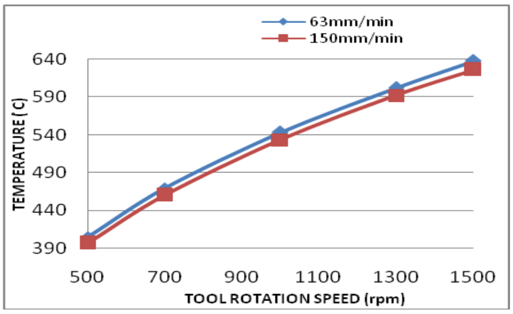
Table.5 Predicted results at constant tool rotation speed and varying tool traverse rate

Sl No.	Tool Rotation (rpm)	Tool Traverse Rate (mm/min)	Peak temperature (^{0}c)	Flow stress (MPa)	Strain rate (1/sec)	Normal Force (kN)
1	700	30	470	73.37	42.9	10.2
2		63	468	73.87	43	10.3
3		150	459.882	77.2	43.38	10.7
4		200	453.89	79.3163	43.57	11.0
5		250	448.25	81.33	43.75	11.3
6	800	30	496.362	68.454	49.0107	9.5
7		63	495.83	68.9487	49.1498	9.6
8		150	486.666	71.9632	49.5106	10.0
9		200	480.331	73.9509	49.7091	10.3
10		250	474.399	75.8567	49.901	10.6

increases (below melting point), decreasing the normal force (Fig.13d) which leads to formation of defects due improper consolidation of transferred material. An opposite effect is observed with increase in tool traverse speed, as the tool traverse speed increases, the peak temperature decreases, increasing the normal force (Fig.14d) which leads to the squeezing out of stirred material forming the voids. Hence an optimum range of axial force is required to be maintained by selecting proper tool rotational and traverse speeds to form of defect free solid state weld.



(a)



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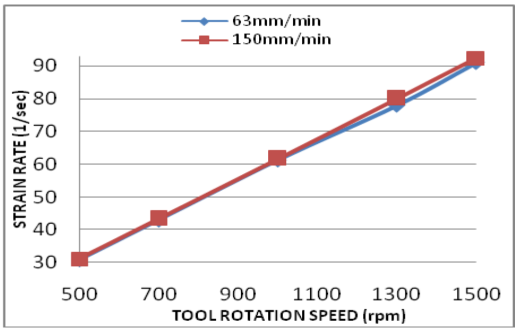

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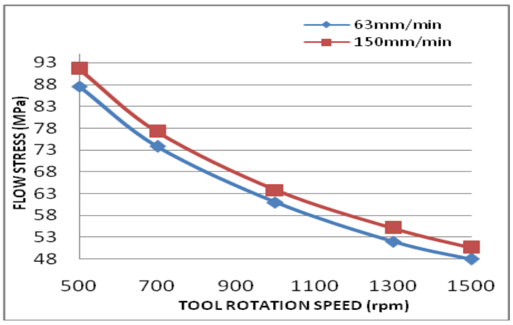
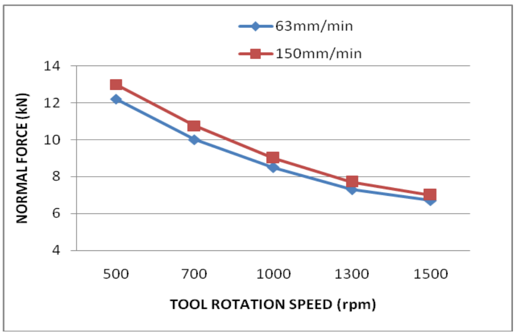
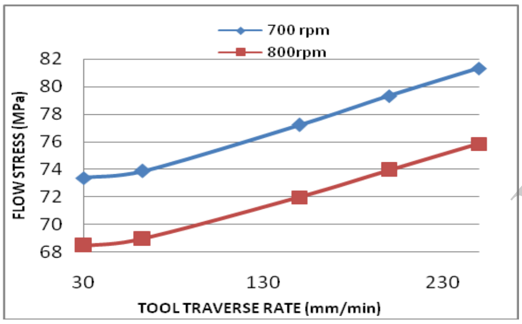


(c)



(d)

Fig.13 Predicted results showing effect of tool rotation speed on: (a) Temperature (b) Strain rate (c) Flow stress (d) Normal Force



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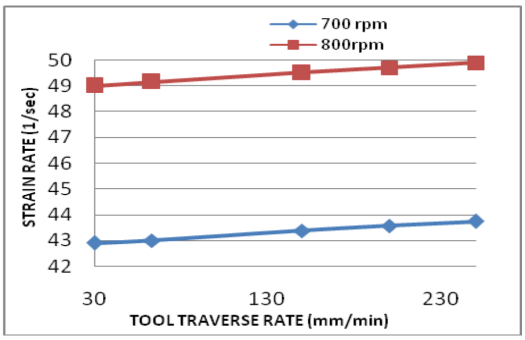

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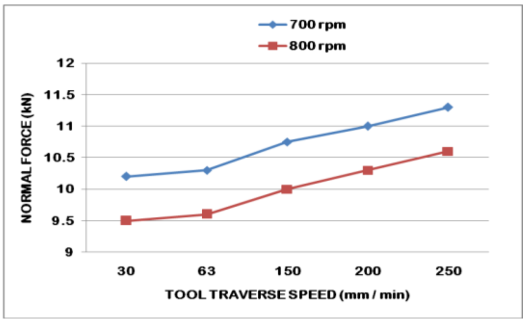

(d)

Fig.14 Predicted results showing effect of tool traverse speed on: (a) Temperature (b) Flow stress (c) Strain rate (d) Normal Force

V. CONCLUSIONS

A combined complementary effort of experimental evaluation and three-dimensional thermo-mechanical modeling of butt joining of Aluminum alloy 6061-T6 is carried out to understand the effect of important process parameters on the formation of good weld. The good agreement between the predicted and measured temperature history and average normal force has been found validating thermomechanical model of FSW. Parametric studies have been conducted to determine the effect of tool rotational and traverse speeds on welding temperature, strain rate and stress. In addition, we have been able to predict the normal force history which depends on strain-rate and temperature – dependent flow stress. The prediction shows that the normal force decreases with increase in the tool rotational speed as the temperature increases decreasing the flow stress and increases with increase in tool traverse speed as flow stress increases. The simulated results will be helpful in determining optimum values of axial force to be maintained by selecting the proper tool speeds for the formation of good weld. The simulated results can also be utilized to predict weld quality by analyzing banded texture of weld bead surface which is formed by influence of axial force through interaction of tool shoulder with base material during FSW.

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