Thermomechanical Modeling and Experimental Evaluation of Friction Stir Welds of Aluminium AA6061 Alloy

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Abstract — The present work involves physical understanding of friction stir weld joint formation and influence of weld process parameters from the combined complementary efforts of experimental examination and numerical modelling. The thermal histories and temperature distributions in the workpiece during Friction stir welding (FSW) process involving the butt joining of aluminium AA6061-T6 alloy is experimentally explored from the devised thermocouple layout to measure the temperature at different locations on the workpiece in the welding direction. The thermomechanical modeling of friction stir welding process is carried out by using general purpose Finite Element Analysis (FEA) simulation tool 'Altair Hyperworks' to evaluate the important physical aspects of FSW. The core process model governs the heat generation by friction between tool and workpiece, plastic deformation and the subsequent thermal history imposed on the material. Thermal and mechanical behaviors are mutually dependent and coupled together to simulate the process close to the real FSW. Further, the simulation model is tested with experimental results, the results of the simulation are found to be in good agreement with that of experimental results, validating the model. It is observed from the analysis that for the constant tool traverse rate and increasing tool rotation speeds the peak temperatures during welding are increased leading to lower flow stresses. On the other hand as the tool traverse rate increases with the tool rotation speed constant, the total heat input decreases which leads to decrease in temperature, increasing the flow stress required for continuous deformation of material for joint formation.

Keywords — Aluminium AA6061 alloy, Friction stir welding, Temperature, Thermomechanical modelling, Tool rotational speed, Welding speed, Flow stresses.

I. INTRODUCTION

Friction stir welding (FSW) is a solid state joining process, a new technique with no melting during welding. The temperatures at which the process is carried out remain below the solidus temperature; hence the welds have superior properties compared to fusion welds. The basic concept of FSW is remarkably simple, in which a non consumable rotating tool with a specially designed pin and shoulder is used for welding. The pin is initially inserted into the joint interface of sheets or plates to be welded and subsequently traversed along the joint line. The tool serves three primary functions; heating of the workpiece, movement of material to produce the joint, and containment of the hot metal beneath the tool shoulder.

One of the main research topics in FSW is the evaluation of the temperature field. Although the temperatures involved in the process are lower than the melting points of the weld materials, they are high enough to promote phase transformations. Thus, it is very important to know the time–temperature history of the welds. Usually, FSW temperature is measured using thermocouples [1, 2, 3]. However, the process of measuring temperature variations in the nugget zone using the technique mentioned above is a very difficult task. Numerical methods can be very efficient and convenient for this study and in fact, along the last few years, they have been used in the field of FSW. Zhu and Chao [4] presented three-dimensional nonlinear thermal and thermomechanical simulations using finite element analysis code – WELDSIM on 304L stainless steel friction stirwelded plates. The total heat input and heat transfer coefficient were estimated 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 three-dimensional 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. Buffa et al.[5] using DEFORM-3D^{TM}, a Lagrangian implicit code modelled the FSW process from the initial plunge state to steady-state travel. A non-uniform mesh with adaptive remeshing was adopted. A rigid-viscoplastic material model was employed and material constants were determined by numerical regression based on experimental data. It was assumed that the 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.

Computational tools could be helpful to better understand and visualize the influence of input parameters on FSW process. Visualization and analysis of the material flow, temperature field, stresses, and strains involved during the FSW process can be easily obtained using simulation results than using experimental ones[6]. Therefore, in order to attain the best weld properties, simulations can help to adjust and optimize the process parameters and tool design.

II. MATERIAL AND METHODS

The friction stir welding was carried out on Eta stir welding machine. The equipment is fully automated with computerised facilities to measure normal force and torque applied during welding. During the experimental process six Aluminium AA6061-T6 alloy plates of dimensions (300x75x5) mm were taken for welding. Three butt joints were obtained and the details are given in table 1.

Table 1

Joint No.	Tool rotation speed(rpm)	Tool traverse rate(mm/min)	Tool used
1	700	63	Tool - 1
2	1000	63	
3	800	150	Tool - 2

Process parameters of experimentation

Two different conical tools made up of H-13 tool steel were used for welding, one of these tools had grooved pin while the other tool had threaded pin, the configuration of these tools are given in table 2 and table 3 respectively.

Table 2

The tool with tapered/ conical grooved Pin

Sl. No.	Description	Specification
1.	Pin length	4.80mm
2.	Pin Diameter	D=4.5mm, d=3mm
3.	Shoulder Diameter	20mm
4.	Shoulder Length	70mm
5.	Tilt angle	2^0

Tool -1 configuration

Table 3

The tool with tapered/conical threaded Pin

Sl. No.	Description	Specification
1.	Pin length	4.80mm
2.	Pin Diameter	D=4.5mm, d=3mm
3.	Shoulder Diameter	25mm
4.	Shoulder Length	70mm
5.	Tilt angle	2^0

Tool -2 configuration

K-type thermocouples were used to measure the temperature during friction stir welding. USB-TC controller a, USB-based 8-channel thermocouple input device is used to connect the thermocouples to a personal computer that contained a data acquisition system installed to record the temperature histories during FSW.

Small holes with a diameter of 0.8mm were drilled on workpiece to accommodate the thermocouples. The layouts are devised to measure the temperature histories in the welding direction. The holes used to accommodate the thermocouple have a depth of at least 3mm. Therefore, the thermocouples were securely embedded in the holes and the temperature can be measured correctly without any external disturbances.The positions of the thermocouples inside the workpiece are shown in Fig 1.

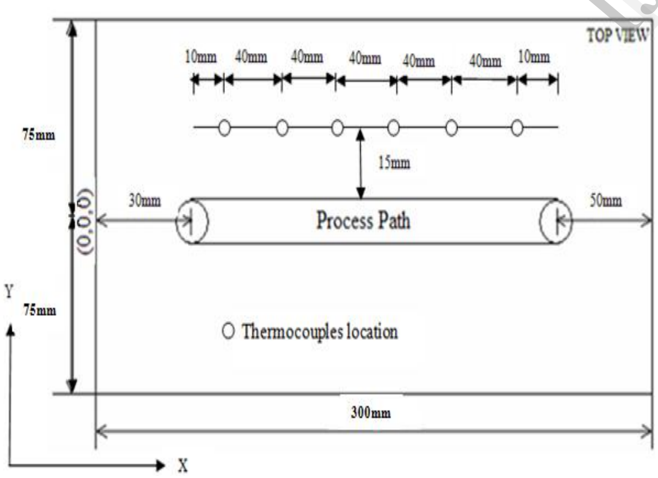

Fig 1 Thermocouple Layout

III. EXPERIMENTAL WORK

A. *Measurement of Normal forces during friction stir welding*

The normal force on the workpiece exerted by tool for three different process parameters as shown in Fig 2 was measured by the load cell setup integrated into the ETA FSW machine Spindle and interfaced with the control system which displays the force as a function of time on the read out screen in console.

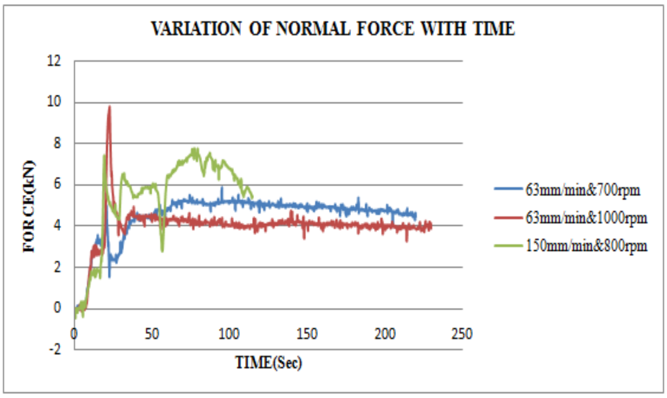

Fig 2 Normal force exerted for 3 different parameters

The normal force varies during the 3 stages of friction stir welding; plunging, dwell period and tool traverse along weld line. Fig 3 shows the variation of normal force during different stages of welding.

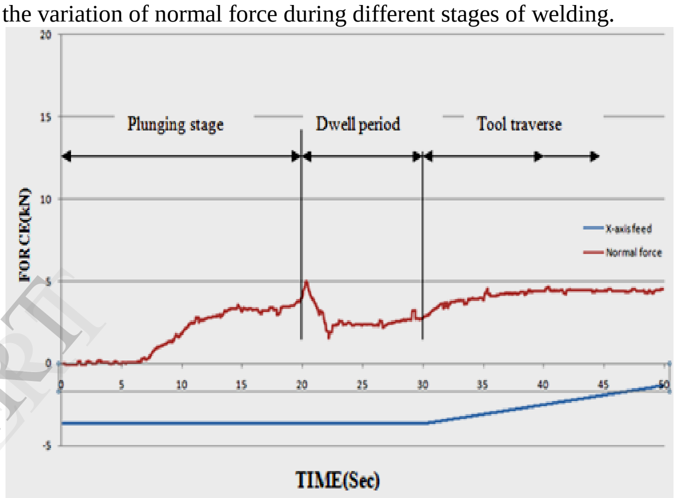

Fig 3 Variation of Normal Force

B. *Measurement of temperature using thermocouples*

A thermocouple layout consisting of three different channels was devised to measure the temperature distribution during welding. The variation of temperature with respect to time at different locations is shown graphically in Fig 4.

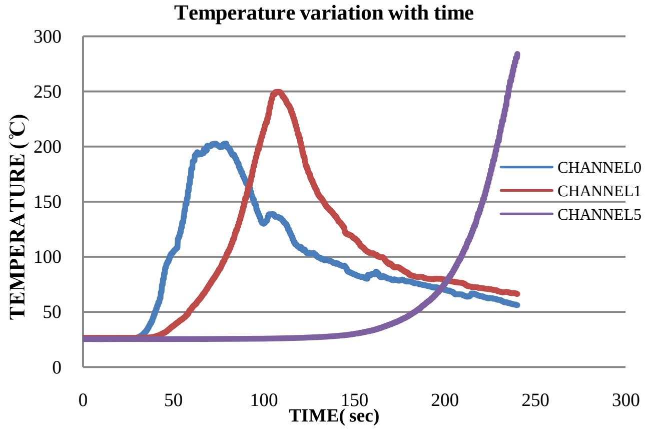

Fig 4 Temperature variation with time in different channels

IV. THEMOMECHANICAL MODELLING

Thermomechanical modeling and simulation of friction stir welding was done using the finite element software. Computer-aided engineering simulation software by name Altair Hyperworks was used for modeling and simulation. A three dimensional thermomechanical model for butt joining of aluminium plates was developed and solved using HyperXtrude solver. The accurate values of temperature fields, strain rate, effective strain and flow stress during the joint formation were predicted for varying range of process parameters.

The thermomechanical modeling and simulation of the Friction stir welding necessitated the thorough description of certain critical parameters, specifying boundary conditions, post processing.

A. Process Modeling Input

Preparing correct input for process modeling is very important. Process modeling input is discussed in terms of geometric parameters, process parameters, and material parameters considered during the friction stir welding process.

B. Geometric parameters

The starting workpiece geometry and the tool geometry need to be defined while modeling a friction stir welding process. The geometric parameters for butt weld joint modeling are length, width and thickness of the plate geometry. Pin diameter, pin height, shoulder diameter and shoulder height are used to define the tool geometry. Fig 5 shows the geometric model developed in the software.

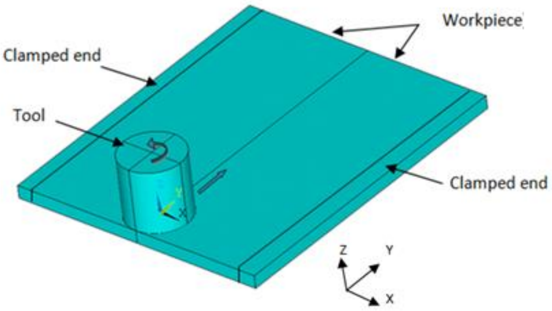

Fig 5 Geometric model developed in the software.

C. Process parameters

The typical process parameters to be considered in a friction stir welding process include,

- The workpiece temperature
- Tool translation speed
- Tool rotational speed
- Coefficient of friction between tool and workpiece
- Normal force applied by shoulder on the workpiece
- Top and bottom surface heat losses

D. Tool and workpiece material properties

In order to accurately predict the temperature fields and metal flow, it is necessary to use reliable input data. Material properties that relate to both heat transfer and deformation need to be defined. 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 behaviour. 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 friction stir welding process.

E. Element Type

Hex20 elements were used for thermomechanical modeling; these elements are 3D (2nd order) hexahedra elements with 20 nodes ordered as shown in Fig 6. It is a coupled field analysis element with both thermal and structural degrees of freedom.

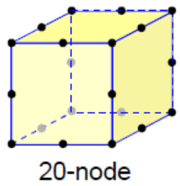

Fig 6 Hex20 elements

F. Boundary Conditions

Tool and workpiece interface conditions

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. Friction stir welding primarily uses viscous dissipation in the workpiece material, driven by high shear stresses at the tool/workpiece interface.

Coefficient friction (μ)

The simplest estimates of Coefficient friction considering a purely rotating tool shoulder (neglecting the translation velocity) by analogy with conventional rotary friction welding, for a slipping contact, the power *q* is given by Equation (1)

$$q = \frac{2\pi}{3}\mu p \omega R_s \quad (1)$$

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).
Modern FSW equipment routinely outputs torque, *T*, normal force, F *as* well as angular velocity, so the total heat input from the machine may be directly estimated from the product *T*ω. Hence we can estimate the coefficient of friction for the simulation in software.
The coefficient of friction used for simulation of FSW process is given in table 4.

Table 4

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

Coefficient of friction considered for analysis

Thermal boundary conditions

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, while the Conduction losses occur from the bottom surface of the workpiece to the backing plate as shown in Fig 6.

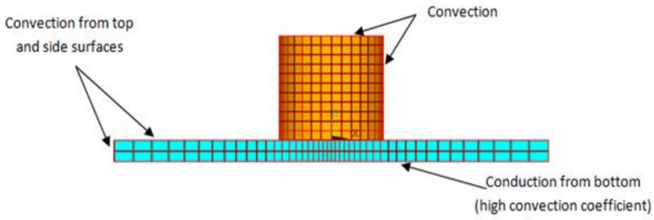

Fig 6 Heat losses in FSW Process

The value of the convection coefficient is 250 W/m^2°C for workpiece and 200 W/m^2°C for tool. This coefficient 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 °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. Because the percentage of heat lost due to radiation is low, radiation heat losses are ignored. An initial temperature of 30 °C is applied on the model. Temperature boundary conditions are not imposed anywhere on the model.

Mechanical boundary conditions

The workpiece is fixed by clamping each plate. 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).

G. *Post Processing*

Post processing is an essentially part of any analysis, henceforth with the necessary parameters described and boundary conditions specified the post processing was carried out in the Hyperworks software and surface temperature contours, surface stress contours, temperature distribution and strain rate distribution were obtained. Fig 7 shows the temperature distribution on top surface of the workpiece during friction stir welding. The heat generated at the tool workpiece interface is conducted to the workpiece ahead of the tool.

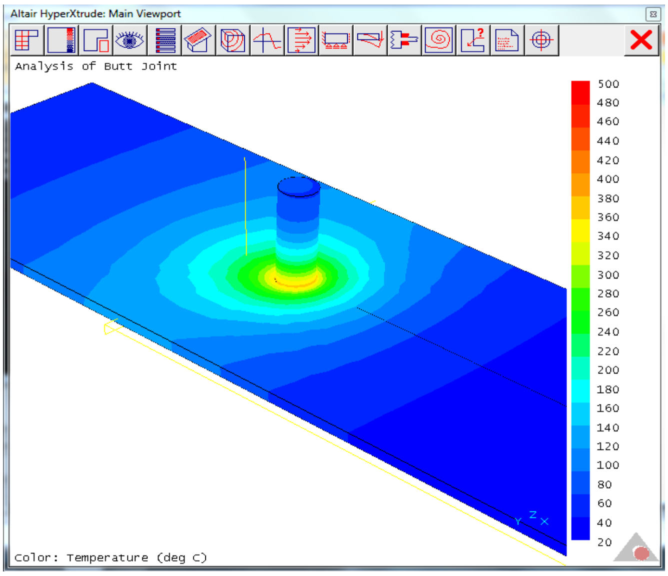

Fig 7 Surface Temperature contours during FSW

V. VALIDATION OF THERMOMECHANICAL MODEL OF FSW

In order to simulate FSW process similar to real time welding and to predict output results accurately model developed using FEA is validated by comparing the experimental results (temperature and force) with that of simulation results.

A. *Validation of Temperature Field*

In friction stir welding the frictional heat and heat developed due to plastic deformation leads to increase in temperature of the workpiece. The temperature distribution in the workpiece simulated using the FEA model is compared with the experimentally measured values. Fig 8 below shows that the FEA temperature results are in good agreement with the experimental temperature results.

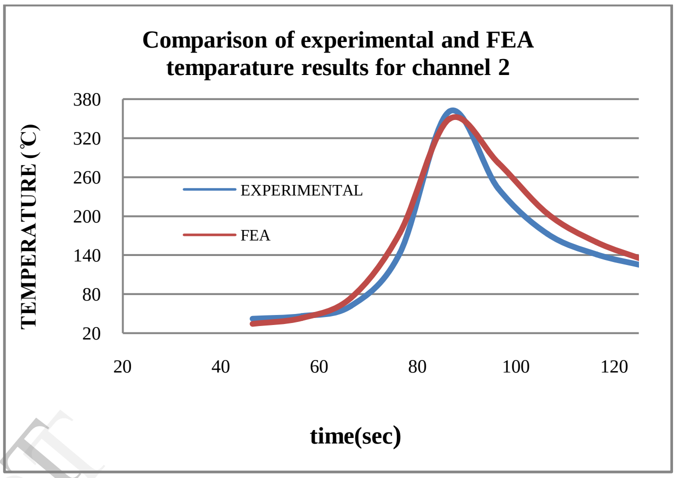

Fig 8 Temperature variation Model 1

B. *Validation Of Normal Force*

The normal force exerted by the tool on the workpiece during welding is measured experimentally and compared with the FEA analysis results to validate the thermomechanical model developed using the Altair Hyperworks. Fig 9 below shows that the FEA results are in good agreement with the experimental results.

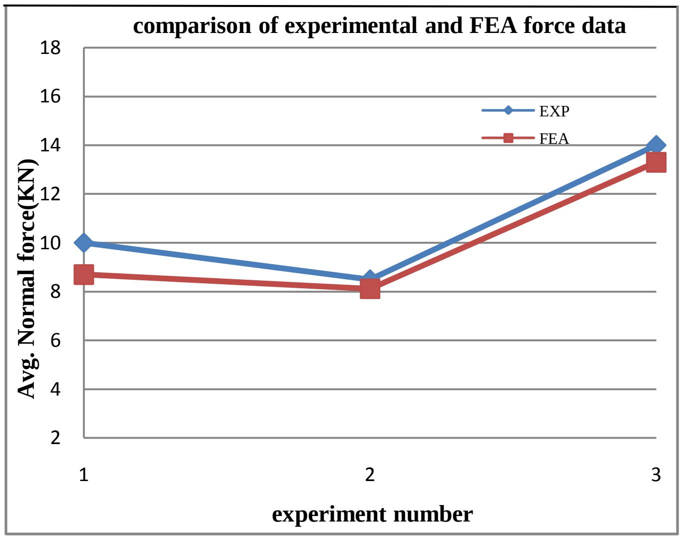

Fig 9 Validation of Normal Force

VI. RESULTS AND DISCUSSION

A three-dimensional thermomechanical model of FSW was developed to simulate the butt joining of Aluminium AA6061 alloy using FEA software 'Altair Hyperworks'. The accurate value of temperature field, flow stress, strain rate and effective strain induced during FSW are predicted for varying tool rotation speed and tool traverse rate by simulating the FEA model.

A. Variation Of Temperature Along The Weld Line During Welding

The temperature during FSW increases as the tool traverses along the weld line. This is due to the cumulative heat added to the work material by the tool action during welding. Fig 10 shows the comparison of temperature along the weld line.

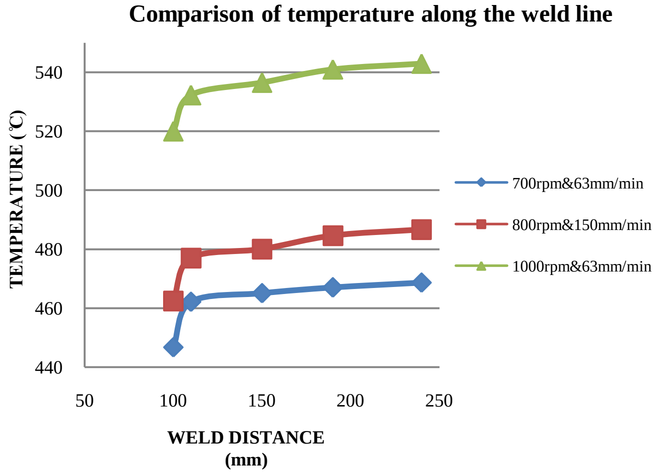

Fig 10 Comparison of temperature along the weld line

B. Variation Of Flow Stress Along The Weld Line During Welding

The flow stress decreases as the tool traverses along the weld line. Fig 11 shows the comparison of flow stress along the weld line.

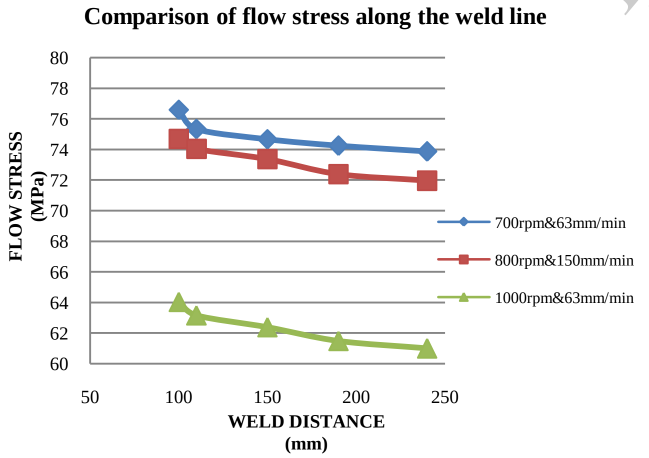

Fig 11 Comparison of flow stress along the weld line

C. Variation Of Strain Rate Along The Weld Line During Welding

It is found from the analysis that the strain rate during friction stir welding is initially high and becomes constant as the tool traverses along the weld line. Fig 12 shows the variation of strain rate along the weld line.

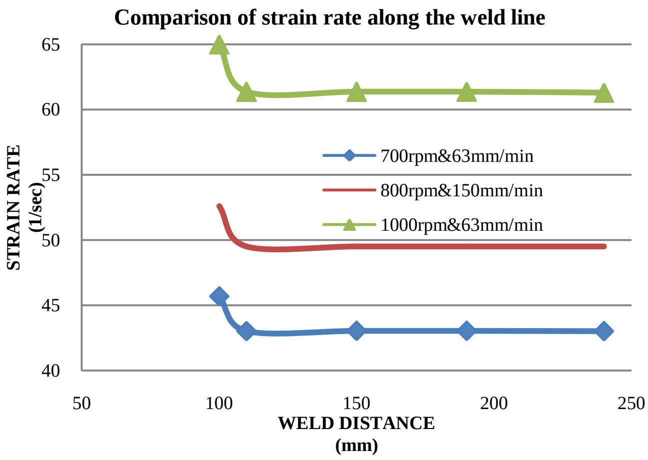

Fig 12 Variation of strain rate along the weld line

D. Variation Of Effective Strain Along The Weld Line During Welding

From the previous section it is evident that the strain rate is high initially along the weld line hence in the above figure the effective strain is less in this region. And as the tool moves along the weld line the effective strain increases and becomes constant. Fig 13 shows the variation of effective strain along the weld line.

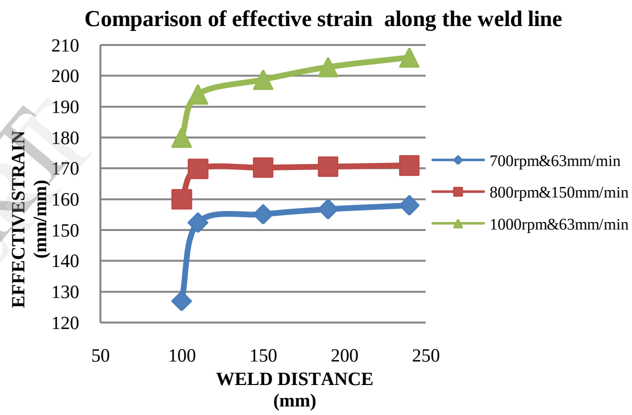

Fig 13 Variation of Effective Strain along the weld line

VII. CONCLUSIONS

A three-dimensional thermo-mechanical model of FSW is developed to simulate the butt joining of Aluminium AA6061 alloy using finite element analysis software 'Altair Hyperworks'. In order to validate the FEA model, the values of temperature distribution and average normal force during simulation are compared with the experimental results. The simulated results are found to be in good agreement with experimental results validating the model. The accurate value of temperature field, flow stress, strain rate and effective strain induced during friction stir welding process is predicted for wide range of process parameters (tool rotation speed and tool traverse rate) by simulating the thermomechanical model of FSW along the weld line.

From the computed results the following conclusions are drawn:

- Significant plastic flow occurs in close proximity of the tool and the temperatures are high in this region leading to low flow stress which is very essential for continuous plastic deformation of work material around the tool pin.

- The temperature induced during friction stir welding increases as the tool traverses along the weld line. This is because cumulative heat is added due to continuous action of tool on the workpiece. Due to increase in temperature, the flow stress required to continually deform the work material decreases.

- The strain rate is initially high and as the temperature increases it becomes almost constant as the tool traverses along the weld line. Due to this the effective strain is less initially and then becomes constant.

- At constant tool traverse rate, the peak temperatures during welding are increased when the tool rotation speeds are increased, which leads to decreased flow stresses at high tool rotation speeds. However very high tool rotational speeds lead to very high temperatures, which results in low strength and defective welds. This phenomenon can be explained by the following two reasons: first, the co-efficient of friction decreases when a local melt occurs, and subsequently decreases the local heat input; secondly, the latent heat absorbs some heat input.
- Higher tool rotational speed resulted in higher heat generation and this led to the excessive release of stirred material to the upper surface in the form of flash, which may produce micro voids in the stir zone.

- As the tool traverse rate increases with constant tool rotation speed, the total heat input decreases, which leads to decrease in temperature for higher tool traverse rate during friction stir welding. Due to decrease in temperature the flow stresses increases. However, when the traverse speed is increased, for a given heat input, there is less time for heat to conduct ahead of the tool and the thermal gradients are larger. At some point the speed will be so high that the material ahead of the tool will be too cold and the flow stress too high, to permit adequate material movement which may result in flaws or tool fracture.

VIII. REFERENCES

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