EFFECT OF PROCESS PARAMETERS ON TEMPERATURE DISTRIBUTION, STRAIN RATE AND FLOW-STRESS DURING FRICTION STIR WELDING OF ALUMINIUM ALLOY

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Abstract

A three dimensional finite element model of friction stir welding was developed by using HyperWorks® codes in order to investigate the effect of process parameters on temperature distribution, strain rate and flow stress in the weld zone of aluminium alloy AA-6061 during the operation. The planning of simulation runs has been performed in accordance with the Taguchi L9 design with three factors-each three levels. The process parameters considered are tool rotation, welding speed and pin tilt angle. Regression analysis is performed in order to investigate the effect of process parameters on response parameters during friction stir welding. A mathematical relationship was also established between input and output parameters. This study indicates that rotational speed is the most significant parameter.

Keywords— *Friction Sir Welding, Aluminium Alloy, Simulation, Temperature, Strain Rate, Flow Stress*

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1. INTRODUCTION

Friction stir welding is a thermo-mechanical based solid state joining process in which a rotational tool is moved about the joining edges of two metallic plates. FSW is fume less welding technology in which there is no need of filler material [11]. The joining is due to softening of metal at edges due to the heat developed by the rotational tool over the surface of metallic plates[12]. In this process, suitable temperature range plays a significant role and which is around 70-90% of the melting point [1]. There are several process parameters based on tool such as Rotational speed, Welding speed, Pin tilt angle, Pin diameter, Shoulder diameter, etc [14].

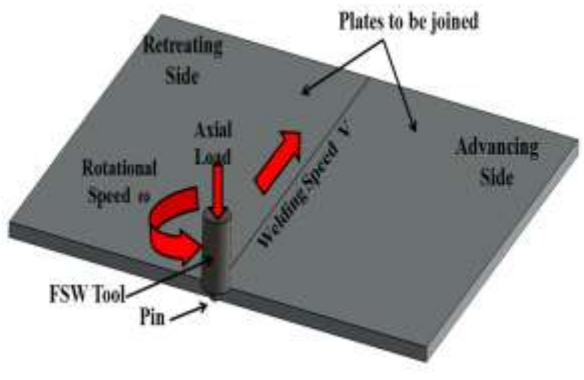

Fig.1 The schematic model of friction stir welding [5]

Abdul Arif, et al. [1] developed a finite element simulation with improved potential for the prediction of temperature during friction stir welding of aluminium alloy. They validated their developed model by comparing the results of with the experimental data. Armansyah et al. [2] performed transient thermal analysis through HyperWorks and they obtained temperature distribution for AA-6061 aluminium alloy and reported that there is decrease in amount of heat generation by increasing constant travelling speed at constant tool rotational speed. M.A. Siddiqui et al. [6] performed simulation for several rotational speeds at two constant sets of transverse speeds by using HyperWorks. They selected lower rotational and transverse speed based on the suitability of machine.. M.A. Siddiqui et al. [7] performed simulation of friction stir welding for the butt joint of Aluminium alloy AA6061 and results were validated with experimental data obtained from work of Zhili Feng et al. [15]. M.A. Siddiqui et al. [8] conducted virtual experiment of friction stir welding through HyperWorks for variable tool rotational speeds with constant travelling speed showed the variation in temperature distribution along the weld line of butt joint. M.A. Siddiqui et al. [9] performed simulation for friction stir welding of aluminium alloy AA-7075 and established relationship among the process parameters which were tool rotational speed and welding and response as maximum temperature. M. Nourani et al. [10] reported that the ANOVA method of the Taguchi L9 design and the full factorial analysis yielded similar parameter contributions. They also optimised the heat effected zone through simulation.

2. PRESENT WORK

In the present work, the effect of process parameters i.e. tool rotational speed (R), welding speed (S) and pin tilt angle (A) on temperature (T), strain rate (Sr) and flow stress

(Fs) during friction stir welding of aluminium alloy AA-6061 is analyzed. The Simulation runs are designed according to Taguchi L9 and the simulation runs are conducted on Altair® HyperWorks®. Regression analysis was performed in order to investigate the influence of process parameters. All other parameters were kept constant. A mathematical relation is also developed for the selected range of parameters.

Aluminum Alloy 6061-T6 is of the 6000 series Aluminum alloys which is mostly used in several application round the world. The physical & thermal properties of Aluminium Alloy AA 6061 is shown in table I [2].

Table 1 Physical & Thermal Properties of AA-6061

Property	Values
Density	2.7g/cm3
Melting Point	582-652ºC
Modulus of Elasticity	68.9GPa
Poisons Ratio	0.33
Thermal Conductivity	167 W/m-k
Specific Heat Capacity	0.869J/g ºC

The material for workpiece and tool are selected with reference to Armansyah et.al [2] for valid combinations. In the present work, two plates of aluminium alloy AA-6061 size 75mm×200mm×6mm is selected. The properties of AA-6061 are shown in Table I. Friction stir welding tool is considered of hot die steel H-13. The shoulder diameter, shoulder length, pin diameter and pin length 15mm, 50mm, 5mm & 5mm respectively are shown in figure 2.

3. DESIGN OF SIMULATION RUNS

Taguchi L9 orthogonal design [3] (shown in Table III) is used to analyze the effect of each processing parameter (the rotational speed, the transverse speed, and the pin tilt angle) on the temperature distribution along the weld line of the friction stir welded joints. This technique is adopted for reducing the number of runs and yields similar contribution as in full factorial design [10].

Table 2 Parameters and their level

S.No	**Parameter**	**Level I**	**Level II**	**Level III**
1	Tool Rotation (R)	500	650	800
2	Welding Speed (S)	4	5	5
3	Pin tilt angle (A)	0	1	2

Table 3 The Taguchi L9 design with three factors-each three levels

Runs	Tool Rotation (RPM)	Welding Speed (mm/s)	Pin Tilt Angle (Degree)
	R	S	A
1	500	4	0
2	500	5	1
3	500	6	2
4	650	4	1
5	650	5	2
6	650	6	0
7	800	4	2
8	800	5	0
9	800	6	1

4. SIMULATION PROCEDURE

In the present work, Manufacturing Solutions module of Altair® HyperWorks® version 12.0 is used for finite element simulation of friction stir welding. HyperWorks® is used for simulation and finite element analysis of friction stir welding process considering the tool as a steady state heat source [4].

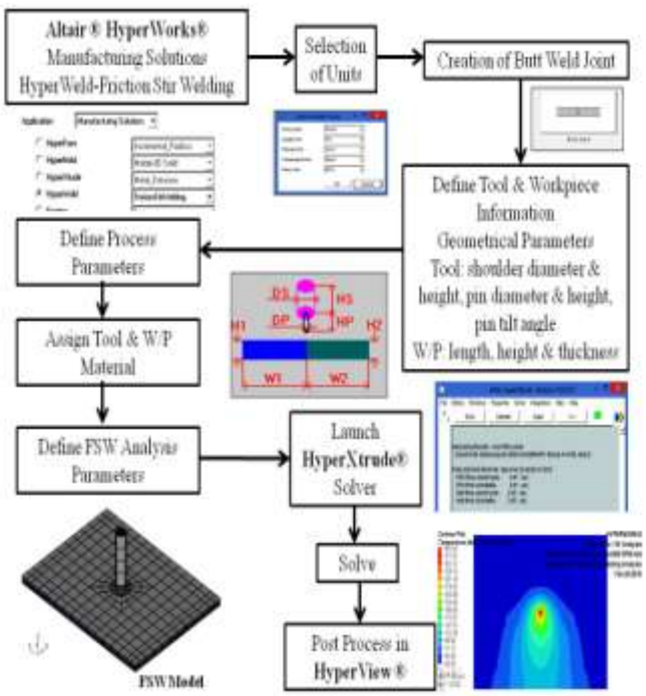

Fig. 2. Flowchart of Friction Stir Welding Simulation

The model has 3200 quadrilateral elements and 3907 active nodes. Hex20 elements were used for thermo mechanical modeling, these elements are three dimensional, 2nd order hexahedral elements with 20 nodes.

Table 4. The Taguchi L9 design with three factors-each three levels, along with the obtained response values from the corresponding runs.

Designation	R (rpm)	S (mm/s)	A (degree)	T (ºC)	Fs (MPa)	Sr (s^{-1})
S1	500	4	0	374.98	60	45.57
S2	500	5	1	369.75	64.08	48.09
S3	500	6	2	391.13	63.12	52.73
S4	650	4	1	441.47	47.91	59.25
S5	650	5	2	445.68	51.5	66.43
S6	650	6	0	406.41	55.11	61.79
S7	800	4	2	497.45	42.05	80.33
S8	800	5	0	454.17	44.47	71.45
S9	800	6	1	458.87	45.28	72.96

5. RESULTS AND DISCUSSSION

5.1 Finite Element Analysis

In the present work, HyperWorks® is used for simulation of friction stir welding process in order to generate butt joint of Aluminium alloy AA6061 plates. This section presents the temperature, strain rate and flow stress pattern developed during friction stir welding.

5.1.1 Temperature

Figure 3 to 5 shows the simulation results of temperature profile obtained through finite element analysis by considering the tool as steady state heat source. It is observed that the temperature distribution is uniform about the centre line or weld line along which the tool is moving.

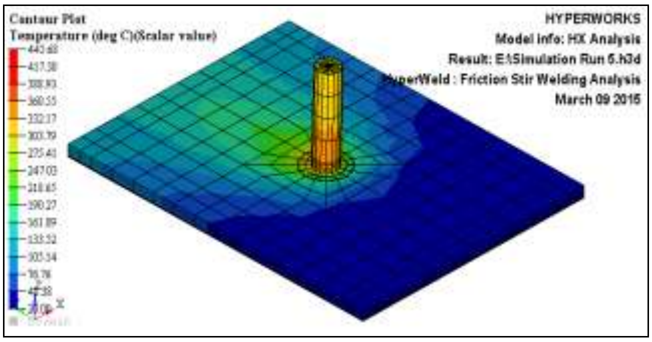

Fig.3 Isometric view of simulated model of butt joint of AA6061 during friction stir welding process showing temperature contours.

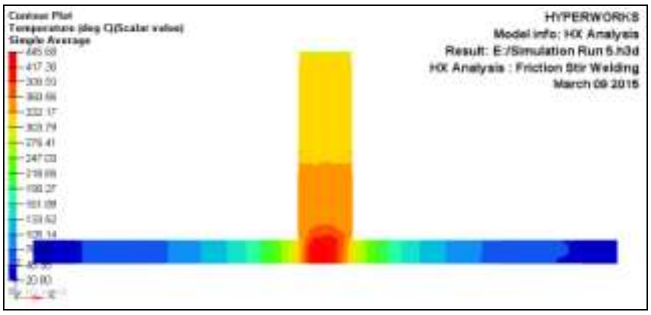

Fig.4 Cross sectional view of simulated model of friction stir welding process showing temperature contours.

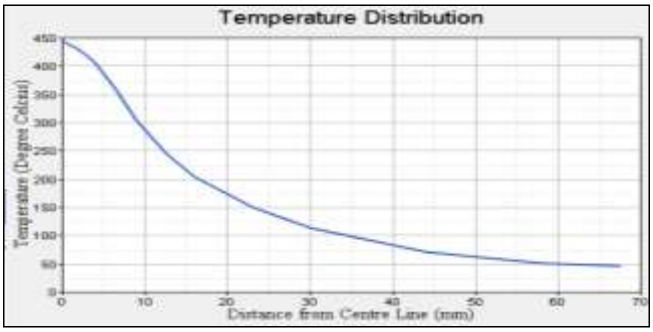

Fig.5 Temperature distribution for advancing side during finite element analysis of friction stir welding with the position of tool in mid of the plates.

5.1.2 Strain Rate

Figure 6 and 7 shows the simulation results of strain rate profile obtained through finite element analysis by considering the tool as steady state heat source. It is observed that the maximum strain is in advancing side of tool and maximum value of strain rate is located near the pin tip circumference which is in contact with the workpiece.

Figure 8 shows the strain rate as a function of distance from the weld line or centre line along which the tool is moving in y direction. It is observed that the strain rate decreases as we move away from centre line as it is directly proportional to the rate of deformation which is maximum at pin workpiece interface.

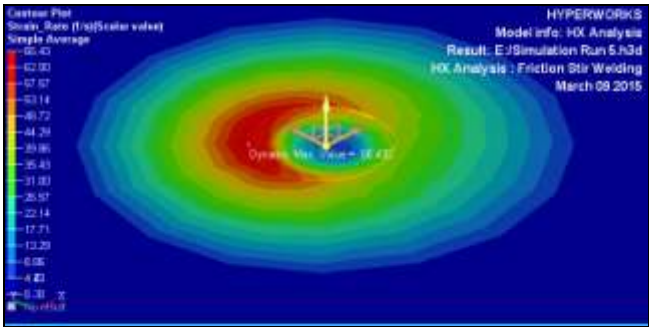

Fig.6 Isometric view of simulated model of friction stir welding process showing strain rate contours near pin workpiece interface with maximum value at periphery of pin.

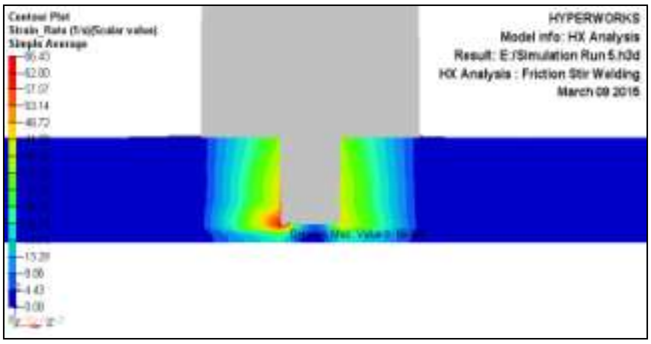

Fig.7 Cross sectional view of strain rate contours observed at pin interface.

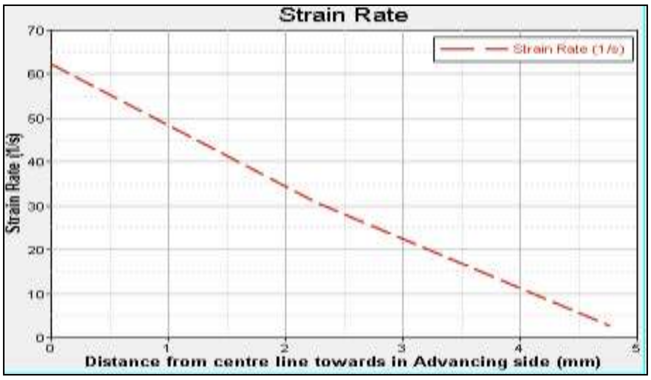

Fig.8 Flow stress distribution as a function of distance from centre line during friction stir welding with tool in mid of the plates.

5.1.3 Flow Stress

Figure 9 and 10 shows the simulation results of flow stress profile obtained through finite element analysis by considering the tool as steady state heat source. It is observed that flow stress is reduced at the centre line through which the tool is transverse.

Figure 11 shows the flow stress as a function of distance from the weld line or centre line along which the tool is moving in y direction. It is observed that the flow stress is minimum below the pin tip as this region has high rate of plastic deformation due to softening of alloy. The graph also shows bulge at advancing side which means flow stress in advancing side is relatively less that retreating side near the centre line.

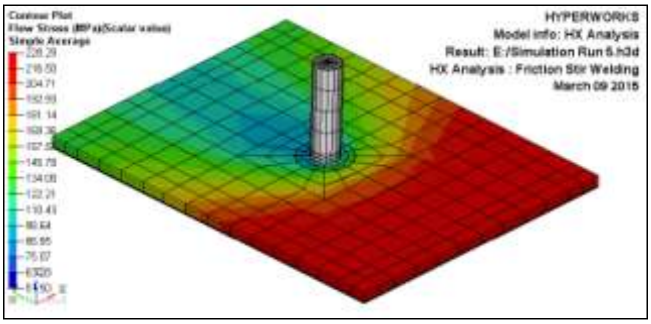

Fig.9 Isometric view of simulated model of friction stir welding process showing flow stress contours.

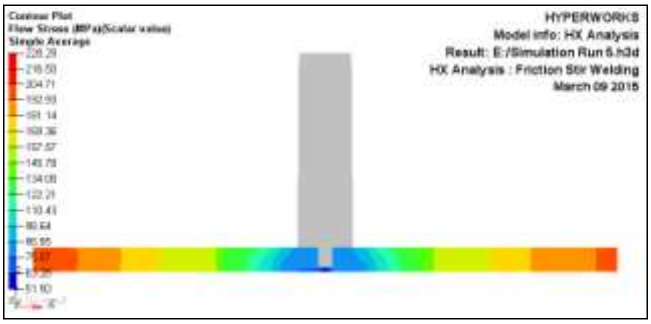

Fig.10 Cross sectional view of simulated model of friction stir welding process showing flow stress contours.

Fig.11 Flow stress distribution as a function of distance from centre line during friction stir welding with tool in mid of the plates.

5.2 Regression Analysis

In friction stir welding process, the sound weld joint depends upon the major responses such as temperature, strain rate and flow stress achieved in tool-work piece interphase. As far as effect of process parameters on responses are concerned, the observations are done on the basis of plots for the data obtained from simulation. The main effect & interaction plots are obtained by statistical tool Minitab [13].

5.2.1 Temperature

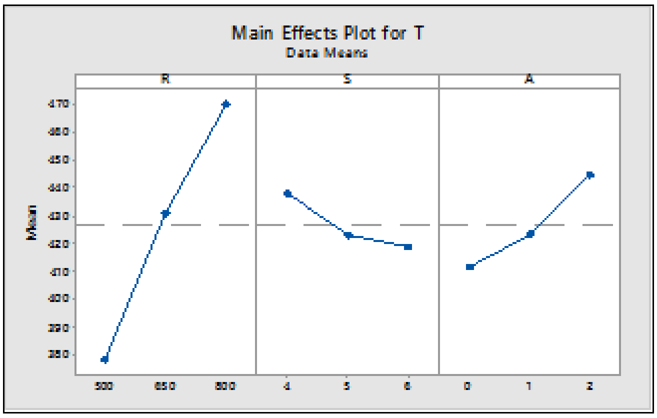

Fig.12 Graphical representation of main effect of Tool rotational speed (R), Welding speed (WS) and Pin tilt Angle (A) on Maximum Temperature during friction stir welding of Aluminium Alloy AA-6061.

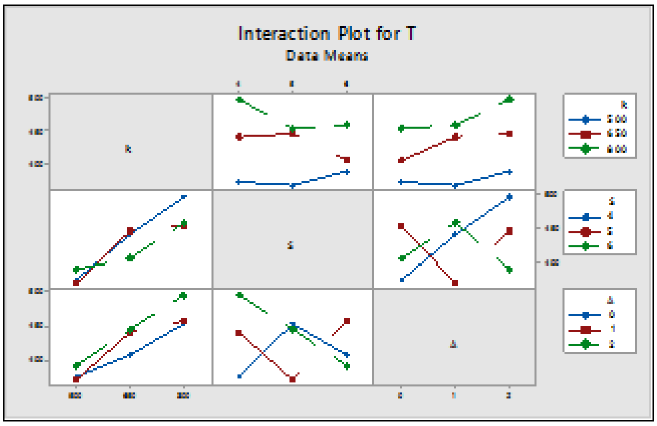

Fig.13 Graphical representation of Interaction effect of tool rotational speed (R), welding speed (S) and pin tilt angle (A) on Maximum Temperature during friction stir welding of Aluminium Alloy AA-6061.

The relationship among tool rotational speed (R), welding speed (S) and pin tilt angle (A) and maximum temperature (T) during friction stir welding of aluminium alloys 6061 is obtained by regression analysis within the range of tool rotational speed (R) of 500-800 rpm, welding speed (S) of 4-6 mm/s and pin tilt angle (A) of 0-2º. The equation or regression model obtained is as follows:

$$T = 259.8 + 0.3051 R - 9.58 S + 16.45 A$$

5.2.2 Strain Rate

Graph (figure 14) shows the main effect of process parameters i.e. rotational speed (R), welding speed (S) and pin tilt angle (A) on Strain rate (Sr).

Graph (figure 15) shows the interaction effect of process parameters i.e. rotational speed (R), welding speed (S) and pin tilt angle (A) on Strain rate.

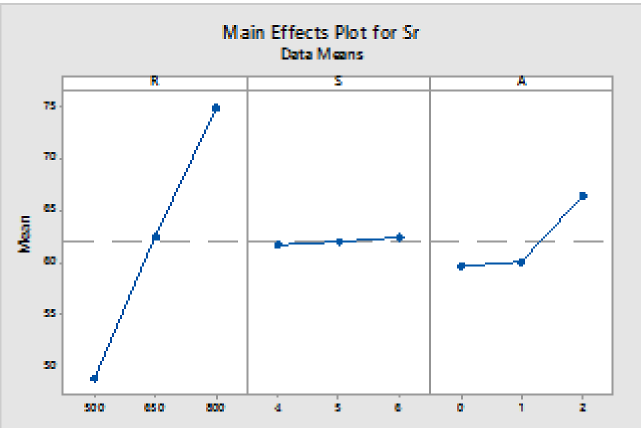

Fig.14 Graphical representation of main effect of Tool rotational speed (R), Welding speed (WS) and Pin tilt Angle (A) on Maximum Temperature during friction stir welding of Aluminium Alloy AA-6061.

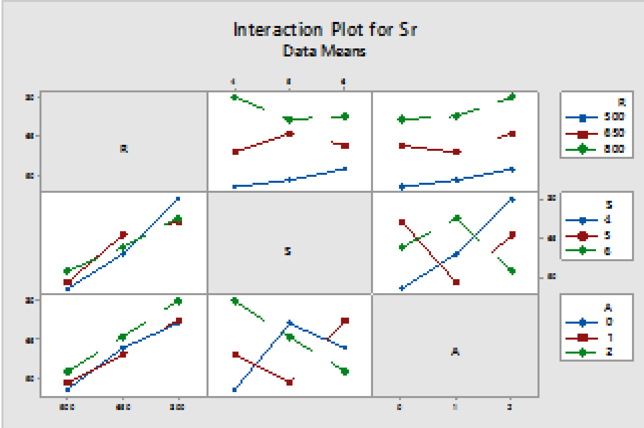

Fig.15 Graphical representation of Interaction effect of tool rotational speed (R), welding speed (S) and pin tilt angle (A) on Maximum Temperature during friction stir welding of Aluminium Alloy AA-6061.

The relationship among tool rotational speed (R), welding speed (S) and pin tilt angle (A) and strain rate (Sr) during friction stir welding of aluminium alloys 6061 is obtained by regression analysis within the range of tool rotational speed (R) of 500-800 rpm, welding speed (S) of 4-6 mm/s and pin tilt angle (A) of 0-2º. The equation or regression model obtained is as follows:

$$Sr = 0.09 + 0.08706 R + 0.388 S + 3.447 A$$

5.2.3 Flow-Stress

Graph (figure 16) shows the main effect of process parameters i.e. rotational speed (R), welding speed (S) and pin tilt angle (A) flow stress.

Graph (figure 17) shows the interaction effect of process parameters i.e. rotational speed (R), welding speed (S) and pin tilt angle (A) on flow stress.

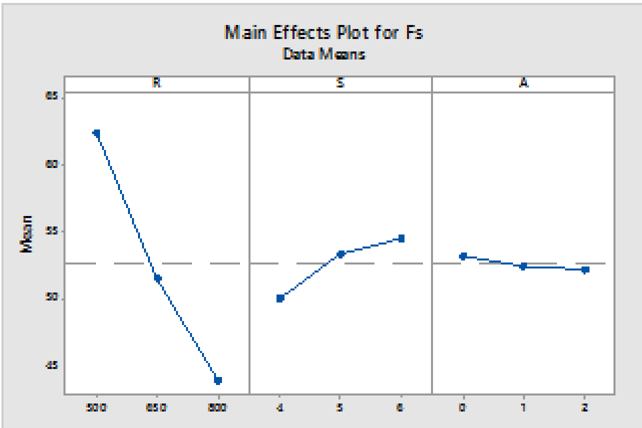

Fig.16 Graphical representation of main effect of Tool rotational speed (R), Welding speed (WS) and Pin tilt Angle (A) on Maximum Temperature during friction stir welding of Aluminium Alloy AA-6061.

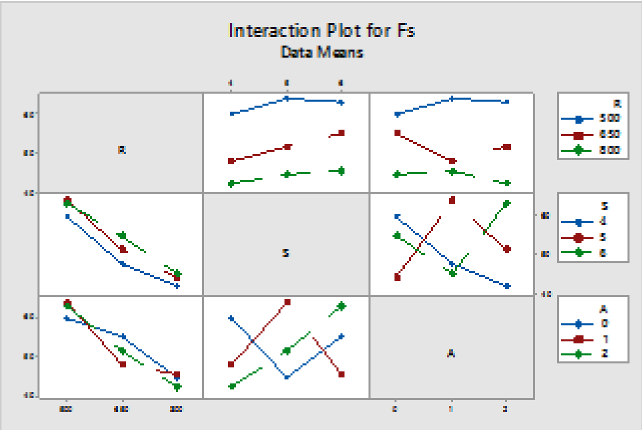

Fig.17 Graphical representation of Interaction effect of tool rotational speed (R), welding speed (S) and pin tilt angle (A) on Maximum Temperature during friction stir welding of Aluminium Alloy AA-6061.

The relationship among tool rotational speed (R), welding speed (S) and pin tilt angle (A) and flow stress (Fs) during friction stir welding of aluminium alloys 6061 is obtained by regression analysis within the range of tool rotational speed (R) of 500-800 rpm, welding speed (S) of 4-6 mm/s and pin tilt angle (A) of 0-2º. The equation or regression model obtained is as follows:

$$\mathbf{Fs = 81.82 - 0.06156\ R + 2.258\ S - 0.485\ A}$$

Table 5. Result summary: Effect of parameters.

Parameters **(increase)**	Temperature (°C)	Strain Rate (1/s)	Flow stress (MPa)
Tool Rotation (rpm)	Increase	Increase	Decrease
Welding Speed (mm/s)	Decrease	Decrease	Increase
Pin tilt angle (degree)	Increase	Increase	Decrease

Table V shows the summary of results obtained from regression analysis of the data obtained for temperature, strain rate and flow stress through simulation of friction stir welding of aluminium alloy. The table shows the effects of parameters.

6. CONCLUSION

In case of friction stir welding process, suitable temperature range, strain rate and flow stress if responsible for successful joining of two alloy plates. In order to analyze the effect of process parameters such as tool rotational speed, pin tilt angle and welding speed on the temperature distribution, the simulation of friction stir welding was performed in accordance with Taguchi L9 orthogonal design. The Regression analysis was performed in order to establish mathematical relation among the parameters can be used for prediction of temperature, strain rate and flow stress during friction stir welding of AA-6061 for the selected range of process parameters. From the ANOVA, it is observed that tool rotational speed has 83.98%, 91.19% and 91.72% contribution on peak temperature, strain rate and flow stress respectively. It is concluded that the most significant parameter is tool rotational speed which has high percentage of contribution on responses.

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