Optimization and Validation of Process Parameters in Friction Stir Welding on AA 6061 Aluminum Alloy Using Gray Relational Analysis

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Abstract

Friction stir welding, a solid state joining technique, is widely being used for joining Aluminum alloys for aerospace, marine, automotive and many other applications of commercial importance. Friction stir welding (FSW) can produce better mechanical properties in the weld zone compared to other conventional welding techniques. FSW trials were carried out using a vertical milling machine on AA 6061 alloy. The main objective of this article is to find the optimum operating conditions for butt joint made of aluminum alloy AA6061. Four major controllable factors each at four levels, namely, rotational speed, welding speed, tool pin length, offset distance are considered for the present study. The uncontrollable factors include ultimate tensile strength, percentage of elongation and hardness which can be converted to signal-to-noise ratios. The gray based taguchi method which is a multiple response process is used to optimize the factors. A gray relational grade obtained from gray relational analysis is used as the multiple performance characteristic. The resulting optimum process parameters are rotational speed at 800 rpm, welding speed at 10 mm/min, pin tool length at 5.7mm and offset distance 0.4mm for the best multiple performance characteristics. Further a three dimensional solid model has been developed using Ansys parametric development language code(APDL) for validation of the experimental results. The results of the simulation are in good agreement with that of experimental results.

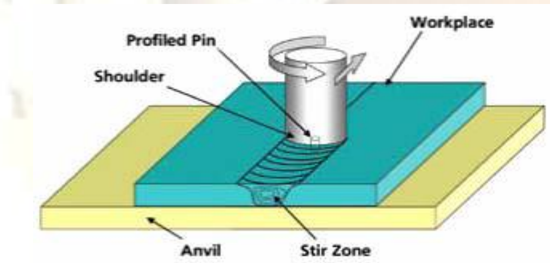
Keywords— Aluminum; Ansys; Friction Stir welding; Gray based Taguchi; Optimization;

1.0. INTRODUCTION

FSW is a novel material joining technique invented by Thomas et al.The welding institute, TWI) in 1991[1]. Material subjected to FSW does not melt and recast and hence the resultant weldment offers advantages over conventional arc weldments, such as better mechanical properties at weld zone and fewer weld defects. In recent years FSW has become one of the most important solid state joining process, and it consumes considerably less energy. No shielding gas or flux is used, thereby making the process environmental friendly.In FSW, as in Elongovan et al. conducted experiments using a non consumable rotating tool with a specially designed pin and shoulder[2]. The heat is generated between the wear resistant welding tool and the material of the work pieces. The heat causes the latter to soften without reaching the melting point and allows traveling of the tool along the welding line. Comparing the velocity of the tool and the time required for the pieces to reach softening temperature, the optimal tool velocity has been provided by Chien et al.[3]. The experimental and numerical evaluation of friction stir welds of AA 6061-T6 aluminum alloy was studied by Prasanna, P. et al.[4]. Finite element modeling for maximum temperature in friction stir welding and its validation has been proved by Prasanna,P.et all [5].The percentage of the generated heat from the tool shoulder or the tool pin was investigated by Song and Kovacevic [6]. The Taguchi technique for the experimental data analysis is a common method used in conventional welding as in Jayaraman.M et al. [7]. The gray-based Taguchi technique for experimental data analysis has been applied to conventional welding by Tarng et al. [8]. As per the available literature, this method has not been applied to FSW. Peel et al. [9]. Chi-hui chien,et all [10] have studied mechanical properties like ultimate tensile stress and percentage of elongation as a function of four parameters like tool rotation speed, transverse, tool tilt angle with respect to the work piece surface and pin tool length. Previous researchers have focused on the different parameters of friction stir welding process like rotational speed, welding speed, tool pin length, tool tilt angle, with cylindrical tool on AA 5083 alloy. In the present work, the butt joint made on AA 6061 alloy by using hexagonal tool profile by considering the controllable factors like rotational speed, welding speed, tool pin length and tool pin offset distance from axis of the shoulder , to show the best multiple performance characteristics by using Gray Relational Analysis(GRA) according to Lin et al [11].The maximum temperature created by FSW process ranges from 70% to 90% of the melting temperature of the work piece material, as measured by the tang et al [12] and col grove et al [13], so that welding defects and large distortion commonly associated with fusion welding are minimized or avoided.

The objective of this article is to study the effects of rotational speed, welding speed (velocity of the tool), pin tool length, tool pin offset distance on the ultimate tensile strength, percentage of elongation and hardness. The four four-level controllable variables are assigned to the L_{16} orthogonal array. The values of uncontrollable variables are converted to signal-to-noise (S/N) ratio performance measures. Taguchi parameter design can optimize the performance characteristics through the setting of process parameters and can reduce the sensitivity of the system performance to sources of variation. The multiple-response process of robustness, the gray-based Taguchi method as in Lin[11]. The statistical method ANOVA is used to interpret the experimental data. Further, the maximum temperate is tested through simulation at optimized parameters using Ansys. The validity of the proposed simulation model is checked with the existing literature as in the tang et al [12] and col grove et al [13].

2.0. Experimental Details:



(a). Friction Stir welding with a rotating tool

(b). Conventional milling (c).Hexagonal tool profile machine

(d). Fabricated Joints (e). Tensile test machine

(f). Hardness test machine

Fig.1. Experimental details

The specimens of the size of 200mmx100mmx6mm were machined from AA6061 aluminum alloy plates. The two plates of AA6061 aluminum alloy were Friction stir welded in the butt configuration by using conventional vertical milling machine. The two plates were placed side by side and clamped firmly to prevent the abutting joint faces from being forced apart. The FSW procedure was based on the TWI procedure described in the patent by Thomas et al.(1991). The experimental set up is shown in Fig.1(a-c). The welding direction of aluminum alloy was along the line of the joint. The rotation of the tool resulted in stirring and mixing of material around the rotating pin and the linear movement of the tool moved the stirred material from the front to the back of the pin and finished the welding process. The insertion depth of the pin into the work pieces was associated with the pin height (length). The tool shoulder contacting the work piece surface depends on the insertion depth of the pin, which results in generation of welds with inner channel, surface groove, excessive flash, and providing small tool pin off set distance from the center of the shoulder will give more heat between the shoulder surface and work piece material.

Totally, 16 FSW joints were produced as shown in fig 1(d-e).Tensile tests were carried based on ASTM standard. The FSW joint plates were sawed into the dimension 200x20mm. The tensile tests were carried out by universal testing machine to find maximum loading and percentage of elongation. Percentage of elongation is defined as ratio of deformation to original length of 50mm. Hardness tests were carried out on Rockwell hardness machine at a force of 60kgf as shown in fig1(f).Properties of aluminum alloy AA 6061 is given in the table.

Table1:% of chemical composition AA 6061 –T6 alloy

Mg	Si	Fe	Cu	Zn	Ti	Mn	Cr	others	Al
0.8 - 1.2	0.4-0.8	0.7	0.15-0.4	0.25	0.15	0.15	0.04-0.35	0.05	98.7

Table2. Mechanical and physical properties of AA 6061 –T6 alloy

Young's modulus	Tensile strength	Ultimate tensile strength
(G Pa)	(M Pa)	(M Pa)
68.9	276	310

Density	Hardness	Melting range	Thermal conductivity	Sp.heat
Kg/m^3	BHN	^{0} C	W/m-k	J/kg-^{0}c
68.9	107	582-652	167	0.896

2.1. Data analysis

2.1.1. Analysis of variance

Analysis of variance (ANOVA) with Taguchi technique as in logothetis [14] or Ross[15] is a statistical method used to interpret experimental data. In this study, there are four primary controllable factors and their four levels are shown in Table 3.Their interactions can be computed from experimental data through ANOVA.

Table3:Important process parameters and their levels

Process parameters	Level 1	Level 2	Level 3	Level 4
Tool rotation speed(rpm)	600	700	800	900
Welding speed(mm/min)	10	14	16	19
Pin tool length(mm)	5.3	5.5	5.7	5.9
Tool pin offset distance(mm)	0.1	0.2	0.3	0.4

As per Taguchi techniques, only 16 experiments for L_{16} orthogonal arrays are needed for percentage of elongation (%) and ultimate tensile strength (MPa) and hardness (BHN). By neglecting the values of the initial and the end pieces from each set of five piece trial under same experimental condition, the resulting averaged elongation rate, averaged ultimate tensile strength and hardness are calculated and are shown in Table 4.

2.1.2. GRAY RELATIONAL ANALYSIS

In the gray relational analysis, data preprocessing is first performed in order to normalize the raw data for analysis. In this study, a linear normalization of the S/N ratio is performed in the range between zero and unity, which is also called gray relational generation as in Tarng et al[8]or Lin [11].The gray relational analysis steps were described as in R.Venkat Rao Springer Series in Advance Manufacturing[16].

Step1: Data pre-processing: if the number of experiments is "m" and the number of responses(i.e. performance characteristics) is "n" then the ith experiment can be expressed as $\eta_i=(\eta_{i1},\eta_{i2},\ldots\ldots \eta_{ij}\ldots\ldots\eta_{in})$ in decision matrix form, where η_{ij} is the performance value(or measure of performance) of response j(j=1,2,3….n) for experiment i(i=1,2,3…m). the general form of decision matrix D is given in eqn (1)

$$D=\begin{bmatrix} \eta_{11} & \cdots & \eta_{1j} & \cdots & \eta 1n \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \eta_{i1} & \cdots & \eta_{ij} & \cdots & \eta_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \eta_{m1} & \cdots & \eta_{mj} & \cdots & \eta_{mn} \end{bmatrix} \qquad (1)$$

Table 4. The FSW process data of L16 orthogonal arrays and their S/N ratio.

Trail No.	Process parameters level				UTS (M Pa)		%elongation		Hardness (BHN)	
	A	B	C	D	UTS	S/N_1	POE	S/N_2	H (BHN)	S/N_3
1	1	1	1	1	116	41.28	12.6	22	81.6	38.23
2	1	2	2	2	120	41.58	16.6	24.4	78.4	37.88
3	1	3	3	3	122	41.72	8.3	18.38	86.2	38.71
4	1	4	4	4	105	40.42	6.25	15.91	87.3	38.82
5	2	1	2	3	107	40.58	10.4	20.34	84.2	38.5
6	2	2	1	4	123	41.79	14.58	23.27	79.4	37.99
7	2	3	4	1	103	40.25	13.3	22.47	80.8	38.14
8	2	4	3	2	80	38.06	5.8	15.26	88.3	38.91
9	**3**	**1**	**3**	**4**	**132**	**42.41**	**23.6**	**27.64**	**77.7**	**37.8**
10	3	2	4	3	112	40.98	9.1	19.18	85.2	38.6
11	3	3	1	2	123	41.86	17.5	24.86	78	37.84
12	3	4	2	1	115	41.21	10.8	20.66	83.3	38.41
13	4	1	4	2	118	41.43	15.8	23.97	78.6	37.9
14	4	2	3	1	116	41.36	11.6	21.28	82.4	38.31
15	4	3	2	4	125	41.93	21.6	26.68	78.2	37.86
16	4	4	1	3	119	41.51	14.1	22.98	80.1	38.07

The term η_i can be translated into the the comparability sequence $X_i=(x_{i1}, x_{i2}, \ldots x_{ij} \ldots x_{in})$, where x_{ij} is the normalized value of η_{ij} for response j(j=1,2,3,….n) of experiment i(i=1,2,3…m). After normalization, decision matrix D becomes normalized matrix D', and is given in eqn(2)

$$D' = \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \quad (2)$$

The normalized values of x_{ij} are determined by using equations **3- 5** which are for beneficial type, non beneficial type and target value type responses, respectively. They are described as follows for i=1,2,…..m and j=1,2,…n:

1. If the expectancy of the response is larger-the better(i.e., beneficial response), then it can be expressed by eqn 3

$$X_{ij} = \eta_{ij} - \min_j \eta_{ij} / \max_i \eta_{ij} - \min_j \eta_{ij} \quad (3)$$

2. If the expectancy of the response is smaller- the better (i.e, non-beneficial response), then it can be expressed by eqn 4

$$Xij = \max_j \eta_{ij} - \eta_{ij} / \max_i \eta_{ij} - \min_j \eta_{ij} \quad (4)$$

3. If the expectancy of the response is nominal-the-best(i.e., closer to the desired value of or target value), the it can be expressed by eqn 5

$$X_{ij} = 1 - \left(\left|\eta_{ij} - \eta_j^*\right| / \left(\max\left(\max\left(\eta_{ij}\right) - \eta_i * \eta_j * - \min\left(\eta_{ij}\right)\right)\right)\right) \quad (5)$$

Where $\eta_j^*$is closer to the desired value of j^{th} response.

In the Taguchi method for the larger the better, the S/N ratio is used to determine the deviation of the performance characteristic from the desired value. The S/N ratio η_{ij} for the i^{th} performance characteristic in the j^{th} experiment for the m observations y_{ij} in each trial can be expressed in eqn 6. The normalization S/N ratio values are tabulated in table 5.

$$\eta_{ij} = -10 \log_{10}(1/m \sum y^{-2}_{ij}) \quad \textbf{(6)}$$

Table 5: The normalized and S/N ratio values for UTS, % elongation and Hardness

Trial number	Ultimate tensile strength (MPA) S/N$_1$	% elongation S/N$_2$	Hardness (BHN) S/N$_3$
Ideal sequence	**1**	**1**	**1**
1	0.74	0.54	0.38
2	0.8	0.73	0.07
3	0.84	0.25	0.81
4	0.54	0.05	0.91
5	0.57	0.41	0.63
6	0.85	0.64	0.17
7	0.5	0.58	0.3
8	0	0	1
9	1	1	0
10	0.67	0.31	0.72
11	0.87	0.77	0.036
12	0.72	0.43	0.54
13	0.68	0.7	0.09
14	0.66	0.48	0.51
15	0.88	0.92	0.054
16	0.79	0.62	0.24

Step2: Reference sequence: For the comparability sequence, all performance values are scaled to (0,1) for a response j of experiment i, if the value X_{ij} which has been processed by data pre-processing procedure is equal to 1 or nearer to 1 than the value for any other experiment, then the performance of experiment 1 is considered as best for the response j. The reference sequence X_0 where x_{0j} is the reference value for j^{th} response and it aims to find the experiment whose comparability sequence is the closest to the reference sequence.

Step3: Gray relational coefficient is used for determining how close x_{ij} and x_i^0. The larger the gray relational coefficient, the closer x_{ij} and x_i^0 are. Table 5 shows the normalized S/N ratio for the ultimate tensile strength and the elongation rate. Basically, the larger normalized S/N ratio corresponds to better performance and the best normalized S/N ratio is equal to unity. The gray relational coefficient is calculated to express the relationship between the ideal (best) and actual normalized S/N ratio. The gray relational coefficient ξij for the i^{th} performance characteristic in the j^{th} experiment can be expressed in Logothetis (1992) [14] as in eqn 7.

Table 6: Gray relational grade and its order of each performance characteristic.

Trial number	UTS (M Pa)	POE (%)	Hardness (BHN)	Gray relational grade	Order
Weighting factor	**0.6**	**0.25**	**0.15**		
Ideal sequence	**1**	**1**	**1**		
1	***0.657***	***0.52***	***0.44***	***0.592***	***10***
2	*0.71*	*0.64*	*0.34*	*0.637*	*6*
3	*0.75*	*0.4*	*0.72*	*0.658*	*4*
4	*0.52*	*0.34*	*0.84*	*0.523*	*13*
5	*0.53*	*0.45*	*0.57*	*0.516*	*14*
6	*0.76*	*0.58*	*0.37*	*0.656*	*5*
7	*0.5*	*0.54*	*0.41*	*0.496*	*15*
8	*0.33*	*0.33*	*1*	*0.430*	*16*
9	1	1	0.33	0.899	1
10	*0.6*	*0.42*	*0.64*	*0.561*	*12*
11	*0.79*	*0.68*	*0.34*	*0.695*	*3*
12	*0.64*	*0.46*	*0.52*	*0.577*	*11*
13	*0.68*	*0.625*	*0.35*	*0.616*	*8*
14	*0.66*	*0.49*	*0.5*	*0.593*	*9*
15	*0.8*	*0.86*	*0.34*	*0.749*	*2*
16	*0.7*	*0.56*	*0.39*	*0.618*	*7*

$$\xi_{ij} = \min_i \min_j \left|x_i^0 - x_{ij}\right| + \xi \max_i \max_j \left|x_i^0 - x_{ij}\right| \Big/ \left|x_i^0 - x_{ij}\right| + \xi \max_i \max_j \left|x_i^0 - x_{ij}\right| \quad (7)$$

For i=1,2,3….m and j=1,2,…n

ξ= Distinguishing coefficient is in the range $0 \leq \xi \leq 1$Distinguishing coefficient (ξ) is also known as the index for the distinguishabilty. It is defined as in the The smaller (ζ) is the higher is its distinguishabity. The purpose of ξ is to expand or compress the range of the gray relational coefficient. Different distinguishing coefficient may lead to different solution results. Decision makers should try several different distinguishing coefficients and analyze the impact on the GRA results.

Step4: Gray relational grade: The measurement formula for quantification in gray relational space is called the gray relational grade. A gray relational grade (gray relational degree) is a weighted sum of the gray relational coefficients and it can be calculated using equation **(8)**

$$\gamma_j = \sum_{i=1}^{m} w_i \, \xi_{ij} \quad (8)$$

where, ξ_{ij} = gray relational coefficient and w_i= weighting factor

γ_j, is the gray relational grade for j^{th} experiment, and m is the performance characteristics. In this article, the weighting factors for the ultimate tensile strength, percentage of elongation and hardness are to be assumed as 0.6, 0.25 and 0.15 respectively. The gray relational grade is shown in Table 6 for the overall performance characteristics from combination of ultimate tensile strength, percentage of elongation and hardness.

Once the optimal level of the FSW process parameters are selected, the final step is to predict and verify improvement of the final step is to predict and verify improvement of the performance characteristic using the optimal level of FSW process parameters. The estimated gray relational grade γ_j as in C.L.Lin (2004)[11] using the optimal level of FSW process parameters can be calculated as in eqn 9

$$\gamma\hat{} = \gamma_m + \sum_{i=1}^{q} (\gamma_i - \gamma_m) \quad (9)$$

where γ_m is the total mean of the gray relational grade, γ_i is the mean of the gray relational grade at the optimal level, and q is the number of FSW process parameters that significantly affect the multiple performance characteristics.

3.0. Finite element model

The thermal and mechanical responses of the material during friction stir welding process are investigated by finite element simulations. In this study, a nonlinear, transient three-dimensional heat transfer model is developed to determine the temperature fields The finite element models are parametrically built using APDL (ANSYS Parametric Design Language) provided by ANSYS® [17]. The models are then validated by comparing the results with optimal experimental data.

3.1.Thermal model

The purpose of the thermal model is to calculate the transient temperature fields developed in the work piece during friction stir welding. In the thermal analysis, the transient temperature field *T* which is a function of time *t* and the spatial coordinates (*x*, *y*, *z*), is estimated by the three dimensional nonlinear heat transfer equation 10.

$$\frac{\partial(\rho c T)}{\partial t} = \frac{\partial}{\partial t}\left(K_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial t}\left(K_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial t}\left(K_z \frac{\partial T}{\partial z}\right) \quad (10)$$

where ρ = Density, Kg/mm^3 C = Specific heat J/Kg^0

K_x, K_y, K_z = Thermal conductivities along x, y and z directions, W/m^0C

T = Absolute temperature, K

Assumptions

A number of assumptions have been made in developing the finite element thermal model, which includes:

- Work piece material is isotropic and homogeneous.
- No melting occurs during the welding process.
- Thermal boundary conditions are symmetrical across
- The weld centerline.
- Heat transfer from the work piece to the clamp is negligible.

3.2 HEAT GENERATION

Accurate modeling of the friction stir welding process is essential to correctly represent heat generation. Modeling heat evolution between the tool and work piece is an important step in understanding how it affects material flow and microstructure modification within and surrounding the weld. For an ideal case, the torque required to rotate a circular shaft relative to the plate surface under the action of an axial load is given by eqn 11.

$$\int_0^{M_r} dM = \int_0^R \mu P(r) 2\pi r^2 dr = \frac{2}{3}\mu\pi PR^3 \quad \textbf{(11)}$$

where M is the interfacial torque, μ is the friction coefficient, R is the surface radius, and P is the pressure distribution across the interface (here assumed constant).

If all the shearing work at the interface is converted into frictional heat, the average heat input per unit area and time becomes in eqn 12

$$Q_1 = \int_0^{M_R} \omega dM = \int_0^R \omega 2\pi\mu \, \mathrm{P} r^2 dr \quad (12)$$

where Q_1 is the net power in watts and ω is the angular velocity in rad/s.

The next step is to express the angular velocity in terms of the rotational speed N [rotations/s]. By substituting $\omega = 2\pi N$ into egn 12,

$$Q_1 = \int_0^R 4\pi^2 \mu PNr^2 dr = \frac{4}{3}\pi^2 \mu PNR^3 \quad \textbf{(13)}$$

From (eqn.13), it is obvious that the heat input depends both on rotational speed and the shoulder radius, leading to a non-uniform heat generation during welding. These parameters are the main process variables in friction stir welding, since the pressure P cannot exceed the actual flow stress of the material at the operating temperature.

In order to describe the heat source in the numerical model, it is more convenient to express the heat generation as a sum of individual contributions by using eqn 14

$$Q_1 = \frac{4}{3}\pi^2 \mu PN \sum_{i=1}^{n} \left(R_i^3 - R_{1-1}^3\right) \quad (14)$$

where R_{i-1} and R_i are as shown in Figure 2.

$$\sum_{i=1}^{n} Q(R_i) = Q_1 \quad (15)$$

Hence, the energy generated from position R_{i-1} to R_i is equal to

$$\Delta Q_1 = \frac{4}{3}\pi^2 \mu PN \left(R_i^3 - R_{i-1}^3\right) \quad (16)$$

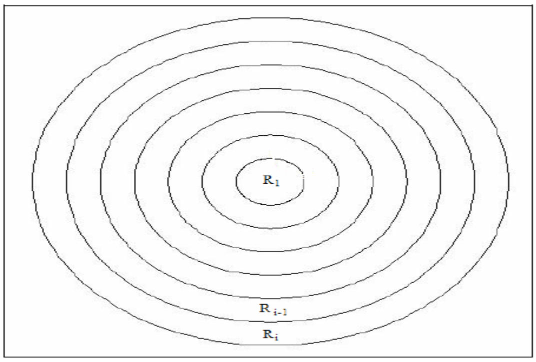


Fig 2. Subdivision of tool shoulder into a series of volume elements of varying strengths.

3.3 Mathematical Description of Moving Heat Source

A moving heat source with a heat distribution simulating the heat generated from the friction between the tool shoulder and the work piece is used in the heat transfer analysis. Using an assumed friction coefficient, Frigaard et al. [18] arrived at a formula for heat generation in their modeling.

A moving cylindrical coordinate system was used for the transient movement of the heat source. Two different values of heat inputs were given to the moving heat source. Q_1 is the heat generated by the shoulder and Q_2 is the heat generated by the pin. Q_1 can be calculated by using (17)

$$Q_1 = \frac{4}{3}\pi^2 \mu PN \sum_{i=1}^{n} \left(R_i^{\,3} - R_{i-1}^{\,3}\right) \quad (17)$$

The heat flow per unit area q_1 of the shoulder can be calculated using (18)

$$q_1 = \frac{3.Q_1.r}{2\pi(R_s^3 - R_p^3)} \quad \text{for} \quad R_s \le r \le R_p \qquad (18)$$

Where N = Tool rotational speed in RPM.
P = Vertical force applied along the shoulder in kN
μ = Coefficient of friction.
R_s = Radius of the shoulder(mm).
R_p = Radius of the tool pin(mm).

The heat generation increases as the distance from the center increases. However, for simplicity a uniform distribution of heat across the surface of the shoulder is assumed. Hence, for uniform distribution the average value of radius of tool shoulder and tool pin was taken,

$$r = \frac{R_s + R_p}{2} \qquad (19)$$

3.4 HEAT GENERATION FROM THE PIN

From Schmidt et al [19], the ratio of heat generated from the pin Q_2, and the heat generated from the shoulder Q_1, was 0.128. Hence heat flow per unit area of the pin q_2 is also 0.128 times q_1. This q_1 and q_2 were given as inputs to the finite element model.

3.5 BOUNDARY CONDITIONS

The boundary and initial conditions that are applied to the heat transfer model [19] shown in Figure 3 are given as follows:
The initial boundary condition for the calculation is

$$T(x, y, z, t) = T_0 \qquad (20)$$

The heat flux boundary condition at the tool and work piece interface is given by

$$k.\frac{\partial T}{\partial n} = q \qquad (21)$$

The convective boundary condition for all the work piece surfaces exposed to the air is

$$k.\frac{\partial T}{\partial n} = h(T - T_0) \qquad (22)$$

where n is the normal direction vector of the boundary.
From (21) and (22) the convection coefficient can be given as $q = h(T - T_0)$
The two plates that were to be welded are assumed identical. At the centerline of the work piece, the temperature gradient in the transverse direction equals to zero due to the symmetrical requirement.

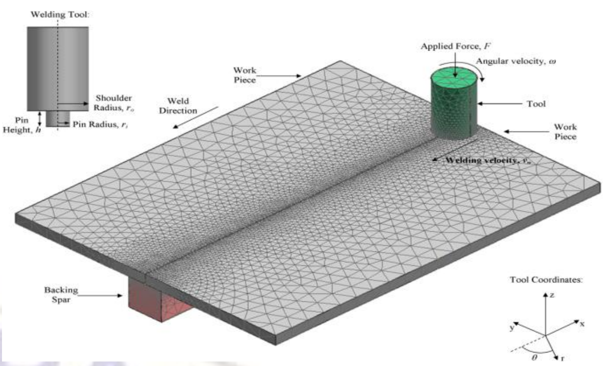


Fig 3.Finite element model of FSW, tool coordinate system and tool geometry

3.6. Simulation

The thermal modeling was carried out in transient thermal analysis used to obtain the maximum temperature through the optimum parameters. According to Tang et al [12] and Col grove et al [13] the obtained maximum temperature 70 to 90% of the melting temperature of the work piece material which indicates that the good quality of weld further it indicates that the weld joint have good mechanical properties.

4.0 RESULTS AND DISCUSSION:

In this study, there are four major controllable factors each one at four levels namely rotation speed(600, 700, 800, 900rpm), Welding speed(10, 14, 16, 19mm/min), pin tool length(5.3, 5.5, 5.7, 5.9mm), tool pin offset distance(0.1, 0.2, 0.3, 0.4mm) as shown in Table 3, which are used for ANOVA. In Table 4, based on Taguchi's recommendation of the larger the better, S/N ratios, S/N_1, S/N_2, and S/N_3, for the ultimate tensile strength and the elongation rate, respectively, were computed by Equation (6) with their corresponding average value. Usually, the ultimate tensile strength is more important than the elongation rate and hardness. Therefore, in this study, the weighting factors for the ultimate tensile strength, the elongation rate and hardness are assumed to be 0.6, 0.25 and 0.15, respectively. In practice, the weighting factor may depend on desired mechanical performance of the products. In Table 5, the gray relational grade is a single index for the overall performance characteristics from the combination of ultimate tensile strength, the elongation rate and hardness. It has been shown that experiment 16 yields the best multiple performance characteristics among 16 experiments because of the highest gray relational grade in Table 6. In other words, the optimal FSW process for the best multiple performance characteristics is, based on the experiment 9, the combination of control factors being A3B1C3D4.

The effect of each FSW process parameter on the gray relational grade at different levels can be separated out because the experimental design is orthogonal. In Table 7, the optimal FSW process for the best multiple performance characteristics is predicted to be the combination of control factors A3B1C3D4 which is a case excluded in the table of L_{16} orthogonal arrays. In this case both experiment and prediction has best combination at 9^{th} experiment. Figure 4 shows the response graph of the gray relational grade, where the larger the gray relational grade, the better are the multiple performance characteristics.

Table 7: Response table for the gray relational grade

Factors / Levels	A	B	C	D
1	0.6025	**<u>0.655</u>**	0.640	0.564
2	0.524	0.611	0.6197	0.594
3	**<u>0.683</u>**	0.649	**<u>0.645</u>**	0.588
4	0.644	0.537	0.549	**<u>0.708</u>**
Max-Min	0.159	0.118	0.096	0.142
Rank	1	3	4	2
Total mean gray relation grade : 0.613				

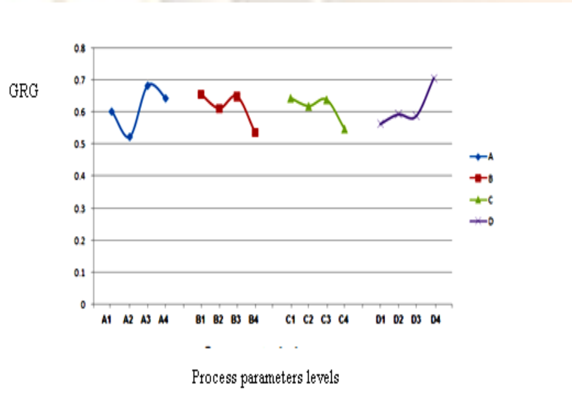


Fig 4: Response Graph For Gray Relational Grade At Different Parameter Levels

ANOVAs summary results of gray relational grade, The accuracy of the gray relational grade for optimal combination of the FSW process parameters with significant effect multiple performance characteristics can be checked by the statistical method ANOVA, Ultimate tensile strength, percentage of elongation and hardness of the joints are functions of and it can be expressed as

$$Y = (N, S, P, O) \quad \textbf{(23)}$$

Where N- Rotational speed (rpm), S- Welding speed (mm/min), P-Pin length (mm), O-Offset distance (mm)

For the four factors, the selected polynomial (regression) could be expressed as in eqn. 24 and values are mentioned in table 8.

$$Y=b_0+b_1N+b_2S+b_3P+b_4O+b_{11}N^2+b_{22}S^2+b_{33}P^2 \; b_{44}O^2+b_{12}NS+b_{13}NF+b_{14}PO+b_{23}SP+b_{24}S0 \quad \textbf{(24)}$$

Table 8: Regression coefficients of UTS, POE and hardness

Regression Coefficients	UTS (MPa)	POE	HARDNESS (BHN)	GRG
b_0	0.851	-5.441	77.7495	-0.7029
b_1	125.2	18.162	7.34103	1.41957
b_2	34.172	17.308	-14.0649	0.34889
b_3	178.5	24.54	7.16008	1.82595
b_4	-185.3	-33.72	1.84252	-1.89921
b_{11}	-28.12	-2.465	-2.71875	-0.299
b_{22}	-3.25	-0.795	0.76875	0.0170625
b_{33}	-15.37	-1.645	-1.71875	-0.173563
b_{44}	21.87	3.770	-0.5875	0.207875
b_{12}	-1.386	-3.853	2.377301	-0.06691
b_{13}	-3.113	-2.556	1.48857	-0.039409
b_{14}	0.035	3.096	-1.623	0.0398441
b_{23}	-39.5	-5.386	0.1625	0.3715
b_{24}	31	2.545	2.45	0.30925

The ANOVA summary results of the gray relational grade, shown in Table 9, indicates that pin tool length, transverse speed, rotation speed and tool pin offset distance are the relatively significant FSW process parameters, respectively, for affecting the multiple performance characteristics.

Table 9: ANOVA Summary of Gray Relational Grade:

Source	Ss	Dof	Ms	F	%contribution
A	0.424	3	0.014	4.27^a	6.76
B	0.053	3	0.018	5.39^a	9.08
C	0.023	3	0.008	2.35	2.79
D	0.245	3	0.082	24.65^a	48.95
ERROR	0.115	35	0.003		32.42
TOTAL	0.48	47			100

This result agrees with the results of the response table for the gray relational grade, as shown in Table7. Based on the previous discussions, the optimal FSW process for the best multiple performance characteristics is predicted to be the case of rotation speed at level 3, welding speed at level 1, tool pin length at level 3, and tool pin offset distance at level 4.

The final step is to predict and verify the optimal FSW process parameter combinations for the best multiple performance characteristics. Yet standard FSW processing parameters are not available in the literature because FSW is a novel material joining technique. From equation (**9**) the estimated gray relational grade using the optimal FSW parameters can then be obtained. Table 10 shows the results of the confirmation experiment using optimal FSW parameters from prediction and experiment.

Table 10: Results of Welding Performance Using the Optimal FSW Process Parameters

	Prediction	Experiment
Level	**A3B1C3D4**	**A3B1C3D4**
Ultimate tensile strength (MPA)	132.9	132
Percentage OF Elongation (%)	24.4	23.8
Hardness(BHN)	76.3	77.7
Gray relational grade	0.92	0.8995

Prediction values found from the present study including ultimate tensile strength **132.9MPa** percentage of elongation **24.4%**, hardness **76.3BHN** and gray relational grade **0.92** were calculated from the polynomial equation 24, and coefficients were taken from the estimated regression coefficient of mathematical model**.**

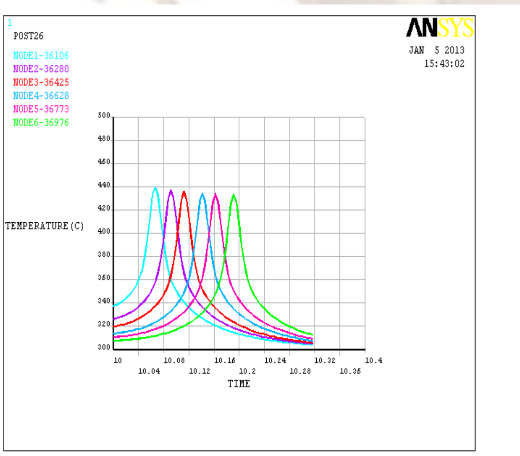


Fig.5 Variation in temperature with distance along the line perpendicular to the weld line on the top surface at node 37643

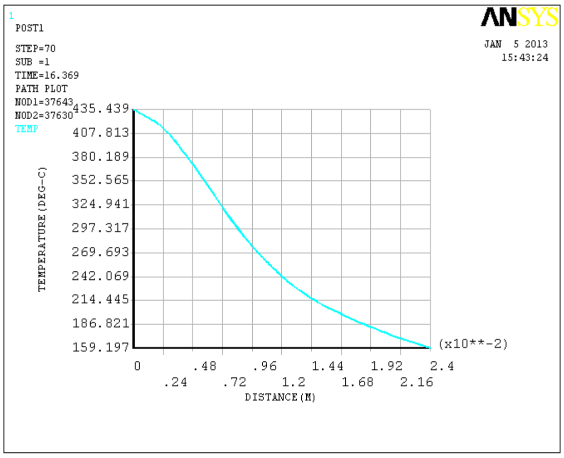


Fig.6 Variation in temperature with time on the top surface

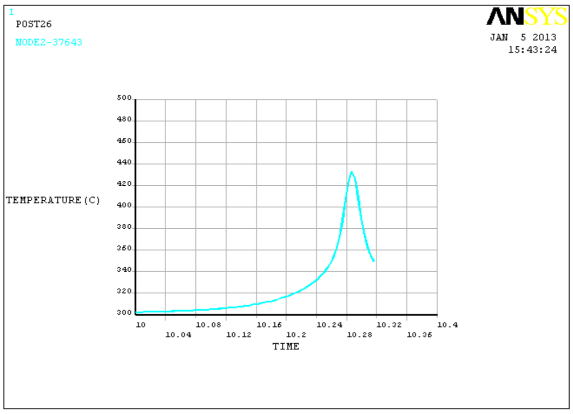


Fig.7 variation in temperature with time along the weld line

From fig 5 shows that predicted maximum temperature for AA 6061 alloy using the APDL programme from Ansys is 435 ^{0}C. It is evident that the peak temperature obtained at the optimal input parameters combination of 800 rpm, 10mm /min, tool pin length 5.7mm and tool pin off set distance 0.4mm. This is about 75% of the melting point temperature of the work piece (580^{0} C). So the quality of the weld is good according to Tang et al [12].

Fig 6.Shows the variation in peak temperature with time along the weld line on the top surface. It indicates that the temperature increases and then decreases with time along the weld line.

It is evident from figure 7 that keeping the optimal parameters constant, the temperature increases with respect to the time. However to attain a good processed zone the optimum operating temperature for material Al6061 is between 420^{0} C and 450^{0} C.

5.0. Conclusions:

The butt joining of Aluminum alloy was successfully carried out using FSW technique. The samples were characterized by mechanical properties like tensile strength, hardness, percentage of elongation, gray relational analysis were done for multi performance characterizations to single response(GRG). The following conclusions were made from the present investigation.

- The optimum operating conditions of FSW have been obtained for two plates of aluminum alloy AA6061 welded in butt joint
- From the experimental results the better performance was occur at 9^{th} experiment that i.e. **A3B1C3D4**,
- The optimal FSW process parameter combinations are rotation speed at 800rpm, welding speed at 10mm/min, tool pin length 5.7mm and offset distance 0.4mm for the best multiple performance characteristics and cost.
- The most significant FSW process parameter is **offset distance** affect the multiple performance characteristics.
- The prediction and experimentation process for the best multiple performance characteristics is the combination with control factors **A3B1C3D4**.
- The maximum temperature is obtained at 435^{0} C through optimized parameters using Ansys. The obtained temperature is about 70 to 90% of the melting point temperature of the parent material. This indicated that the quality of weld is good.

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