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Optimisation of hardness and tensile strength of friction stir welded AA6061 alloy using response surface methodology coupled with grey relational analysis and principle component analysis

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Abstract

The present work aims to optimize the operating parameters such as rotational speed, welding speed and tool diameter for maximum Hardness and Tensile strength of the friction stir welded joint on AA6061 alloy. Three factors with five level response surface design matrix were developed by using MINITAB14 software package. Response Surface Methodology (RSM) was adopted to develop mathematical model between the response and process parameters. Grey relational Analysis (GRA) was deployed to convert multi objective case into single objective one by calculating Grey Relational Grade (GRG). The weights of the influencing parameters were calculated using Principle Component Analysis (PCA). The optimum process parameters are obtained from Response surface plots drawn for GRG. Confirmation tests proved that the proposed methodology has been yielded the optimum process parameters.

Keywords: Friction Stir Welding; Response Surface Method; Grey Relational Analysis; Grey Relational Grade; Principle Component Analysis

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1. Introduction

The Welding Institute (TWI) of UK developed the momentous solid- state joining technique known as Friction stir welding (FSW) in 1991, in which heat is produced due to the interaction of the work piece surface and the tool is responsible for the desired welding. As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally friendly was discussed by Misra et al. (2005). The friction stir welding (FSW) technology is going to become a very important new tool in the aircraft and automotive industry solving more of the problems related to the need of high-performance joints. The joints produced by this method were found to be error free and had excellent mechanical and corrosion properties (By et al., 2012). The stirred zone (SZ) (Sua et al., 2005), the thermo mechanically affected zone (TMAZ) and the heat-affected zone (HAZ) (Leal et al., 2008) were the distinct zones produced during the friction stir welding process (Janjic et al, 2012; Ma et al., 2002). The material flow behavior was predominantly influenced by FSW tool profiles, tool dimensions and FSW process parameters has been investigated by Rai et al. (2011). The FSW was initially applied to aluminum alloys due to their applicability as energy-saving structural material in advanced applications. Owing to its acceptable strength to weight ratio, corrosion resistant and superior properties led them to deploy in transport industries, such as automobiles, trains, aircrafts, etc (Thomas et al., 1993). FSW is useful in the joining of aluminum alloys (6XXX & 7XXX series) which were traditionally difficult to weld as the fusion welding techniques produce brittle dendrite structures leading to steep decrease in the mechanical properties (Cavaliere, 2013).

Elatharasan and Senthilkumar (2013) studied UTS and YS of the friction welded AA6061-T6 alloy joints. Optimization was carried out by using RSM. Elangovan et al. (2009) applied response surface method (RSM) to optimise four process parameters and tensile strength for AA6061. Rajakumar et al (2011) deployed statistical tools such as Analysis of Variance (ANOVA) and

Response Surface Methodology (RSM) to optimize the FSW parameters. Palnivel et al. (2012) used response surface methodology for FSW modelling and optimization. The grey relational analysis proposed by Deng (1982) in which grey relation grade was calculated to convert a multi objective function into a single objective one is widely applied in various applications. The grey relation grade (GRG) was obtained by assigning weights to performance characteristics depending upon their importance (Jangra, et al., 2011; Lin, 2004; Vijayan et al., 2010; and Sharma et al., 2011)

From the available literature it was elucidated that the response surface method was the widely used optimization technique for FSW and Grey relation analysis converts a multi objective function into a single objective function. In Grey relational analysis the GRG can be estimated by assigning weights to the performance characteristics deploying PCA technique which is a widely used one. Hence, the present work aims to optimize the FSW process for maximum hardness and tensile strength varying rotational speed, welding speed and pin diameter by coupling RSM, GRA and PCA.

2. Experimental Procedure

2.1 Experimental Setup

The following scheme of experimental set up is used for FSW on AA6061 plates. The set up consists of a computer controlled FSW machine (Figure 1) with proper welding tool and necessary fixtures for holding the tool. The tool rotational speed ranges from 500-2200 rpm. Initially the rotating pin is inserted into a predrilled hole, which will facilitate the start up of welding. The tool pin profile selected for the present work is “circular” and the material is High Speed Steel. In order to have longer weld length to facilitate representative results, welding was done along the 120 mm length which is perpendicular to the direction of rolling of the test pieces and AA6061 Aluminum Alloy plate was taken on the advancing side and the retreating side.

2.2 Selection of operating parameters

Selection of process parameters in Friction Stir Welding is critical as the properties of the yielded joints merely rely on them. From the past studies it was evident that the Rotational Speed, Welding Speed and Pin Diameter were important influencing parameters in FSW. Hence one need to find the optimum working conditions for efficient joint preparation. Elangovan and Balasubramanian (2008) studied FSW of AA6061 with 15, 18 and 21 mm shoulder diameter tools and reported that the tool with 18 mm shoulder diameter produced defect-free welds irrespective of pin geometries. The operating parameters selected for the present work are shown in Table 1. The tools used in the present work are shown in Figure 2 and the FSW specimen is shown in Figure 3.

Table 1 Welding parameters and tool dimensions

S.No	Process Parameters	Values
1	Rotational Speed(rpm)	800,950,1100,1250,1400
2	Welding Speed(mm/sec)	0.5,0.6,0.7,0.8
3	Axial Force(Kg)	6000
4	Pin Length(mm)	5.3
5	Tool Shoulder Diameter(mm)	18
6	Pin diameter/diagonal(mm)	4,5,6,7,8

Figure 1 FSW machine

Figure 2 Tools used

2.3 Evaluation of Mechanical Properties

Hardness test was carried out using Vickers pyramid hardness testing machine with load of 5 kg. Hardness survey along the transverse direction of the weld was conducted with hardness measurements at regular intervals of 4 mm from the centerline of the weld on both sides of the weld. Tensile tests were conducted on transverse specimens made as per ASTM-E8 cut from heat treated base metal and weld coupons. Stirred Zone strength of the joint was calculated by conducting tensile tests with Universal Testing machine. Scanning Electron Microscopic (SEM) images were taken for estimating the quality of weld (Figure 4). From the SEM images uniform weld bead geometry was observed throughout the specimen.

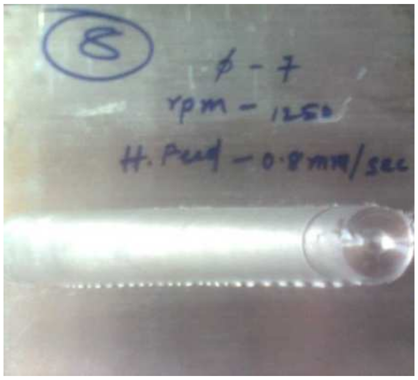

Figure 3 Friction welded specimen

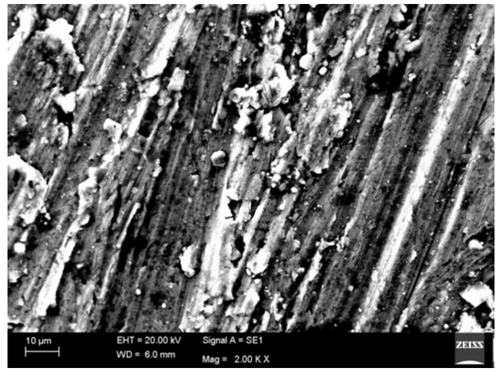

Figure 4 SEM Image

2.4 Experimental Design

The experiments are devised based on central composite face centered design. Central composite design(CCD) matrix with the star points being at the center of each face of factorial space is used. The “face- centered CCD” involves 20 experimental observations at three independent input variables.

Table 2 Experimental design with results

Expt. No	Rotational Speed rpm	Welding Speed mm/min	Pin Dia. mm	Hardness	Tensile strength
1	950	36.25	5	85.94	120.00
2	1250	36.25	5	84.06	99.16
3	950	48.75	5	86.89	164.83
4	1250	48.75	5	90.09	102.16
5	950	36.25	7	81.34	138.16
6	1250	36.25	7	84.31	105.33
7	950	48.75	7	82.02	106.16
8	1250	48.75	7	82.23	82.50
9	800	42.50	6	72.90	135.16
10	1400	42.50	6	78.00	77.83
11	1100	30.00	6	80.00	119.16
12	1100	55.00	6	90.95	136.80
13	1100	42.50	4	83.40	115.30
14	1100	42.50	8	83.09	103.30
15	1100	42.50	6	90.48	135.30
16	1100	42.50	6	95.53	140.25
17	1100	42.50	6	94.91	130.12
18	1100	42.50	6	91.95	135.80
19	1100	42.50	6	92.01	143.50
20	1100	42.50	6	93.00	129.21

Table 3 Normalised values and Deviational Sequence

Experiment Number	Normalised Values		Deviational Sequence	
	Hardness	Tensile Strength	Hardness	Tensile Strength
1	0.576226	0.484713	0.423774	0.515287
2	0.493151	0.245172	0.506849	0.754828
3	0.618206	1	0.381794	0
4	0.759611	0.279655	0.240389	0.720345
5	0.372956	0.693448	0.627044	0.306552
6	0.504198	0.316092	0.495802	0.683908
7	0.403005	0.325632	0.596995	0.674368
8	0.412285	0.053678	0.587715	0.946322
9	0	0.658966	1	0.341034
10	0.225365	0	0.774635	1
11	0.313743	0.475057	0.686257	0.524943
12	0.797614	0.677816	0.202386	0.322184
13	0.463986	0.43069	0.536014	0.56931
14	0.450287	0.292759	0.549713	0.707241
15	0.776845	0.660575	0.223155	0.339425
16	1	0.717471	0	0.282529
17	0.972603	0.601034	0.027397	0.398966
18	0.841803	0.666322	0.158197	0.333678
19	0.844454	0.754828	0.155546	0.245172
20	0.888202	0.590575	0.111798	0.409425

3. Proposed Methodology

3.1 Response surface methodology (RSM)

The Response Surface Methodology (RSM) was adopted for modelling and analysis of process parameters in the FSW in order to obtain mechanical properties of welded joint. In the RSM, the quantitative form of relationship between desired response and independent input variables can be represented as follows:

$$Y = F(R_s, W_s, D) \tag{1}$$

where *Y* is the desired response and *F* is the response function (or response surface). In the procedure of analysis, the approximation of *Y* is proposed using the fitted second-order polynomial regression model which is called the quadratic model. The quadratic model of *Y* can be written as follows:

$$Y = a_0 + \sum_{i=1}^{4} a_i X_i + \sum_{i=1}^{4} a_i X_i^{\,2} + \sum_{i=1}^{4} a_{ij} X_i X_j \tag{2}$$

3.2 Grey relational analysis

Grey Relational Analysis (GRA) is used to determine the optimum condition of various input parameters to obtain the best quality characteristics (Meenu Gupta and Surinder Kumar, 2013; Peng Wang et al, 2013; Radhakrishnan Ramanujam et al, 2011; Senthilkumar, N. et al, 2014).

Grey relational analysis is broadly applied in evaluating or judging the performance of a complex project with meagre information. Within the range of sequences to acquire exact solutions one has to preprocess the data which are related to group of sequences called as Grey relational generation (Deng, J.L. 1989). Preprocessing raw data is a process of converting an original sequence into a decimal sequence between 0.00 and 1.00 for comparison. If the expected data sequence is of the form ‘‘Higher-the-better’’, then the original sequence can be normalized as,

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{3}$$

If the expectancy is the smaller the better, then the original sequence should be normalised as follows

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{4}$$

However to achieve a definite target value, the original sequence will be normalized as follows

$$x_i^*(k) = 1 - \frac{\left| x_i^0(k) - x^0 \right|}{\max x_i^0(k) - x^0} \tag{5}$$

Where $x_i^*(k)$ is sequence after data processing, $x_i^0(k)$ is the original sequence, min $x_i^0(k)$ is the smallest $x_i^0(k)$, max $x_i^0(k)$ is the largest $x_i^0(k)$ value, min $x_i^0(k)$ is the smallest $x_i^0(k)$ value and x^0 is the desired value. Normalised values for the experimental combinations are shown in Table 3.

Generally the grey relational coefficient is represented as $\xi(k)$ and can be calculated as follows:

$$\xi(k) = \frac{\Delta_{\min} + \xi\Delta_{\max}}{\Delta_{0i}(k) + \xi\Delta_{\max}} \tag{6}$$

where, called the deviation sequence is the absolute value of the difference between $x_i^0(k)$ and $x_i^*(k)$. ξ is the distinguishing coefficient. In general, ξ is assumed to be 0.5.

From the grey relational coefficient, the grey relational grade is calculated as follows.

$$x_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \tag{7}$$

For practical applications, the weighting value can vary based on the experimental response quality. Then the equation becomes the following:

$$x_i = \frac{1}{n}\sum_{k=1}^{n} \omega_k \xi_i(k) \tag{8}$$

Where ω_k is the weighting factor for k. In the present investigation, the weighting value ω_k for each parameter is estimated via PCA.

3.3 Principal Component Analysis (PCA)

GRA was found to be an effective tool for converting a multi objective case into a single objective one during optimisation, however allocation of equal weightage to all the components was the major setback in the method. Hence PCA is adopted to estimate weightage of individual components. PCA was initially developed by Pearson (1901) and Hotelling (1993) to explain the variance and covariance structure of a set of defined variable by linearly combining them. The great combination of input variables and output responses is predicted by normalizing the data in PCA.

The Grey Relational coefficients are used to formulate variance covariance matrix S as follows

$$S = \begin{matrix} x_{1,1} & x_{1,2} & \cdots & x_{1,n} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m,1} & x_{m,2} & \cdots & x_{m,p} \end{matrix} \tag{9}$$

Where, n is number of quality characteristics, and m is number of experiment runs, x is grey relational coefficient of each quality characteristic.

The correlational coefficient array can be evaluated as follows

$$R_{jl} = \left(\frac{Cov(X_i(j), X_i(l))}{\sigma_{x_i(j)} \times \sigma_{x_i(l)}} \right), \text{ j= 1,2……..,n l=1,2,3………,n} \tag{10}$$

where Cov($x_i(j)$, $x_i(l)$):the covariance of sequences $x_i(j)$ and $x_i(l)$; σ_{xi} (j):the standard deviation of sequence $x_i(j)$; σ_{xi} (l):the standard deviation of sequence $x_i(l)$.

The eigenvector and Eigen values are calculated from the correlation coefficient array:

$$(R - \lambda_k I_m)V_{ik} = 0 \tag{11}$$

Where λ_k is Eigen values $\sum_{k=1}^{n}(\lambda_k) = n$, k= 1,2……n; $V_{ik} = [a_{k,1}, \quad a_{k,2} ...... \quad a_{k,m}]^T$; the Eigen vectors correspond to the Eigen values, λ_k . The obtained are Eigen values shown in table 4 and Eigen vectors are shown in Table 5.

The variance contribution for the second principal component characterizing the whole original variables, i.e. the two performance characteristics, is as high as 77.2%. Hence the squares of its corresponding eigenvectors are selected as the weighting values of the related performance characteristic and are shown in Table 5.

Table 4 Eigen values and explained variation

Principal Component	Eigen Values	Explained Variation
First	5.122881	0.227929
Second	12.12512	0.772071

Table 5 Eigen vectors for principal components

Quality characteristics	Eigen vector	
	First principle component	Second principle component
Hardness	-0.87868	0.477419
Tensile Strength	0.477419	0.878676

4. Results

The experiments were conducted as per the DOE plan. The optimization was performed for GRG which is the indicating response for the two experimental results. The GRC and GRG for the experimental runs are shown in Table 6. Response surface methodology was adopted to optimize process parameters based on GRG, the regression equation is given in Equation 12 and the corresponding R^2 value is 86.1%. The analysis of variance (ANOVA) is usually applied to summarize the tests performed.

Table 6 Grey Relational coefficients and Grey Relational Grade

Experiment Number	Grey Relational coefficient		GRG
	Hardness	Tensile Strength	
1	1.082516	0.984943	1.007183
2	0.993197	0.796922	0.841659
3	1.134052	2	1.802625
4	1.350642	0.819441	0.940517
5	0.887277	1.239846	1.159485
6	1.004216	0.84466	0.881028
7	0.911581	0.851522	0.865211
8	0.919358	0.691409	0.743365
9	0.666667	1.189012	1.069954
10	0.784538	0.666667	0.693533
11	0.842988	0.975664	0.945424
12	1.423718	1.216273	1.263556
13	0.965238	0.935182	0.942033
14	0.952642	0.828335	0.856668
15	1.382829	1.191291	1.234948
16	2	1.277908	1.442494
17	1.896104	1.11239	1.291021
18	1.519302	1.199504	1.272395
19	1.525447	1.341971	1.383791
20	1.634525	1.099596	1.221522

$$GRG=0.0096\ R_s+0.3635\ W_s+1.7275D-0.1037D^2-0.0265\ W_s\ D-16.4004 \quad (12)$$

4.1 ANOVA analysis

ANOVA technique was used to test the adequacy of the developed response model. As per this technique, if the calculated value of the F_{ratio} of the developed model is less than the standard F_{ratio} (from F-table) value at a desired level of confidence (say 99%), then the model was said to be adequate within the confidence limit. ANOVA test results were presented in Table 7, it is understood that the developed Response surface model was found to be adequate at 99% confidence level.

Table 7 Analysis of Variance for GRG

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	1.22695	1.22695	0.136327	6.88	0.003
Linear	3	0.45018	0.33503	0.111676	5.63	0.016
Square	3	0.47126	0.47126	0.157087	7.92	0.005
Interaction	3	0.30550	0.30550	0.101834	5.14	0.021
Residual Error	10	0.19828	0.19828	0.019828		
Lack-of-Fit	5	0.16008	0.16008	0.032015	4.19	0.071
Pure Error	5	0.03820	0.03820	0.007641		
Total	19	1.42522				

4.2 Optimisation process

The three dimensional response surfaces for GRG were drawn. Response Surface plots clearly indicate the optimal response point. Figure 5(a) to 5(c) shows the three dimensional response surface plots for GRG obtained from the regression model with various pin diameters of 4 mm, 6 mm and 8 mm respectively. The optimum GRG was exhibited by the apex of the response surface.

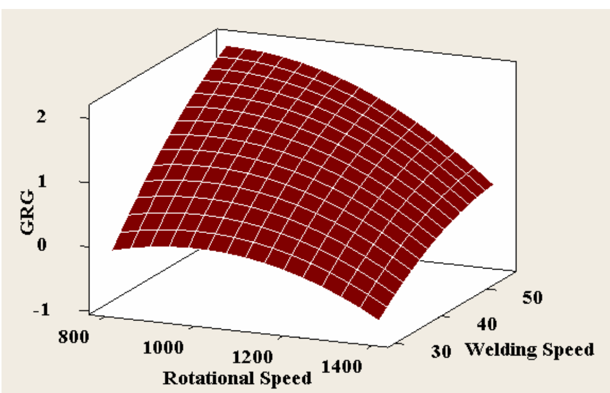

Figure 5(a) 4 mm diameter

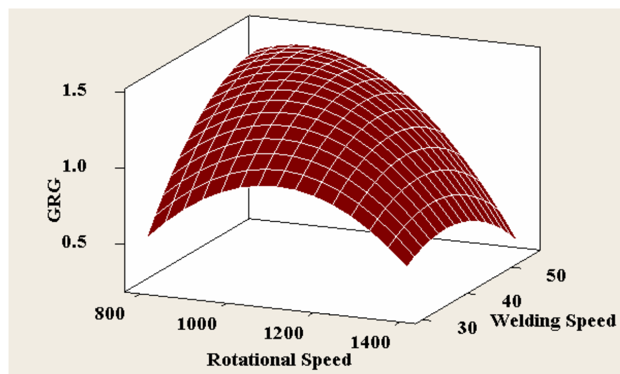

Figure 5(b) 6 mm diameter

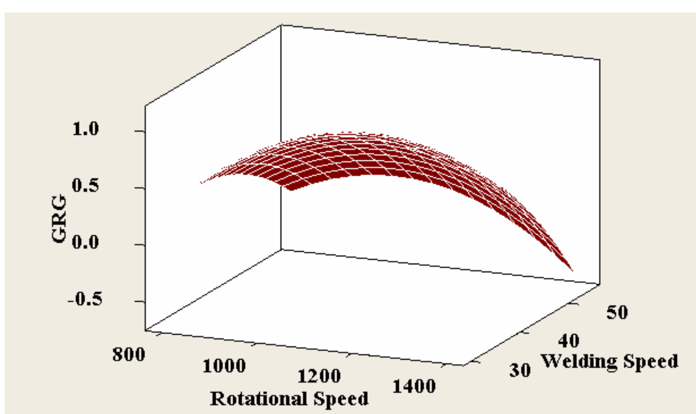

Figure 5(c) 8 mm diameter

Figure 5. Three dimensional response surface plots for GRG

From the response graphs, it can be observed that in Figure 5 the higher GRG values were obtained i.e. for a tool diameter of 4mm. it can also be observed that at the rotational speed of 800 rpm, welding speed of 50 mm/min the GRG is higher indicating the maximum hardness and tensile strength. This can be addressed due to the formation of equiaxed finer grains resulted because of increased work tool interface and the increased heat input associated with the use of speeds. The optimum conditions identified from the response surface plots are 4 mm tool diameter, 800 rpm rotational speed and 50 mm/min welding speed. Experimental test is conducted with the obtained optimum process parameters, the results were compared with the optimum values in the experimental design matrix and are shown in Table 8. It was observed that the enhancement in hardness is 4.96% and the tensile strength increased by 12.32%. The two performance characteristics of Friction Stir welded AA6061 alloy was clearly improved with the proposed methodology.

Table 8 Comparison of results

Parameter	Optimum values in the experimental matrix	Values obtained with the optimum parameters	% change
Hardness	93	98.95	6.39
Tensile strength	164.83	192.2	16.60

5. Conclusions

A five level, three factor full factorial design matrix based on the central composite rotatable design technique was used to study the parametric analysis of AA6061 alloy welded by Friction Stir welding process. The process parameters varied were Speed, welding speed and tool diameter, the responses observed are predict the hardness and tensile strength. Response surface method was adopted to optimize the process parameters. GRA was implemented to obtain the unique objective i.e. GRG and the weight values were estimated deploying Principle Component Analysis (PCA).

From the response plots it is clear that the optimum process parameters were welding speed 800 rpm, rotational speed 50 mm/min and 4 mm tool diameter. The experimental test with the optimum process parameters yielded optimum results proving that the method deployed is accurate. The hardness of the joint is improved by 6.39% and the tensile strength is enhanced by 16.60 %.

Nomenclature

RSM Response Surface Method
GRG Grey Relation Grade
GRA Grey Relation Analysis
GRC Grey Relation Coefficient
PCA Principle Component Analysis
FSW Friction Stir welding
ANOVA Analysis of Variance
UTS Ultimate Tensile Strength
YS Yield Strength
DOE Design of Experiments
CCD Central Composite Design
SEM Scanning Electron Microscope

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Biographical notes

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