International Journal of Advanced Technology and Engineering Exploration, Vol 5(44)
ISSN (Print): 2394-5443 ISSN (Online): 2394-7454
http://dx.doi.org/10.19101/IJATEE.2018.544002

Research Article

Multi objective optimization in friction stir welding using Taguchi orthogonal array and grey relational analysis

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Abstract
Friction stir welding (FSW) is a recent and effective solid state joining technique for joining similar and dissimilar metals. In this communication FSW is carried out on mating pieces made of aluminum alloys AA5083 and AA6061 having dimensions of 65×60×6 mm. An attempt has been made to optimize the process parameters of FSW for Hardness and Toughness of weld bead using Taguchi Technique and grey relation analysis (GRA). In this study, 3 parameters: rotational speed, tool transverse speed and tool depth are considered with 3 levels. Consequently L9 orthogonal array is constructed and 9 experiments are performed to employ aforementioned optimization technique. Taguchi technique and GRA is analyzed in MINITAB software to find out the optimum value of process parameters and observe their contribution. From this study is found that contribution of rotation speed is higher for hardness and contribution of plunge depth is higher for toughness.

Keywords
Friction stir welding (FSW), AA5083, AA6061, Hardness, Toughness, Taguchi, Grey relational analysis (GRA), L9 Orthogonal array, Optimization, MINITAB.

1.Introduction
In fusion welds the chemical composition of melt catches more attention, and fillers or consumable electrodes may be used. Also process may require a neutral atmosphere to avoid the oxidation of melt. Sometimes surface preparation before welding is also essential. Several defects and difficulties due to the melting and solidification come to pass, resulting in weakness of mechanical properties such as tensile strength, fatigue properties and formability. Solid state welds are the processes in which the joint is formed below the melting temperature of material. Therefore, the oxidation does not occur and there is no need for shield gas, neutral atmosphere, and consuming material. One of the solid state welding is friction stir welding. Friction stir welding (FSW) is a material joining process. FSW is highly important and recently developed joining technology that produces a solid phase bond. It is particularly appropriate for the welding of high strength alloys. Main characteristic of FSW is to join material without melting. FSW enables to weld almost all types of aluminium alloys, even non-weldable by fusion welding owing to hot cracking and poor solidification micro structure in the fusion zone.

FSW is observed to be the most significant development in metal joining in a decade and is a “green” technology due to its energy efficiency, environment friendliness, and versatility. In FSW a cylindrical shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces butted together. Frictional heat is generated between the welding tool and work pieces without reaching the melting point. Tool traverse along the weld line and plasticized material is transferred the front edge of the tool to back edge of the tool probe. A non-consumable friction stir welding tool of hardened steel or carbide consists of a shoulder, normal to the axis of rotation of the tool, and a pin. The shoulder diameter is relatively larger than pin diameter to prevent highly plasticized material from being expelled from the joint. It also controls the depth of the pin and helps to create additional frictional heating above the work piece surfaces and minimizes the formation of gaps in the welding area. Friction stir welding tool of stainless steel used in this project having tool tip length of 4mm, tool tip diameter of 3mm and shoulder diameter of 24.8mm as shown in *Figure 1*.

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Figure 1 Stainless Steel tool of FSW

When the tool is moved along the abutting edges, the localized heating softens the material which makes it flow around the pin and a combination of tool rotations and translations lead to movement of material from the front of the pin to back of the pin, where the workpieces compound together to weld.

Process Parameter

1. Tool design- The design of tool is a crucial factor to improve the quality of the weld and the maximum possible welding speed. Tool material should be strong, tough and hard wearing at welding temperature.
2. Tool rotational speed- Generation of friction between tool and work piece depends on Rotational speed which influences the weld quality.
3. Welding feed speed – As welding feed speed increases, temperature decrease at local position.
4. Axial force- Axial force for welding increases with material thickness.
5. Plunge depth **-** Plunge depth is an important process parameter for generating good quality welds with even tool shoulders. The injection depth of pin is directly related with the pin length.

Objectives

1. Analyze the effects of process parameters on hardness and toughness of weld bead
2. Optimize the hardness and toughness of weld bead.

In this study, 3 process parameters are considered in 3 levels to construct L9 orthogonal array and consequently 9 experiments are performed in FSW. These experiments are tested for hardness and toughness on machines as shown in *Figure 2 and 3* respectively.

Figure 2 Rockwell hardness machine

Figure 3 Impact test for toughness

Tutar et al. [1] focused on the parameters influencing the welding in FSW and found the optimal combination of welding parameters: plunge depth, tool rotational speed and dwell time.

Zhao et al. [2] studied microstructural characterizations and mechanical properties in underwater friction stir welding of aluminium and magnesium dissimilar alloys.

Aval [3] searched on microstructure and residual stress distributions in friction stir welding of dissimilar aluminium alloys focus on distribution of residual stress and temperature.

Mittal and Gaurav [4] observed the tensile behaviour of aluminium plates (5083) welded by friction stir welding pertaining to welding parameters: rotational speed, welding speed and pin diameter.

Muruganandam and Das [5] focussed on mechanical properties evaluation and predicting the process parameters by varying rotational as well as welding speeds of friction-stir welding for the dissimilar aluminium alloys ie., between 6xxx (Al-Mg-Si) and 7xxx (Al-Zn-Mg).

Reddy and Reddy [6] highlighted the principle of FSW and main factors that influence the quality of weld.

Magesh et al. [7] conducted research on microstructure and hardness of aluminium alloy-fused silica particulate composite and concluded that the hardness value of the fused silica reinforced LM13 alloy matrix composites increased with the increased addition of fused silica particulates in the matrix.

Ramprasad [8] focussed on weld joint properties of Al 6Al 6061+ 20% SiC metal matrix composite of 6mm thickness plates welded with friction stir welding process.

Devaiah et al. [9] did parametric optimization of friction stir welding parameters using taguchi technique for dissimilar aluminium alloys (AA5083 and AA6061).

Elatharasan and Kumar [10] focused on the parameters which influence the welding joint and found that maximum tensile strength was exhibited by the friction stir welded joints fabricated with the optimized parameters of 2300 r/min rotational speed, 35 mm/min welding speed and tool tilt angle 0.

Optimization

In the present work optimization is carried out using Taguchi technique and grey relational analysis. Taguchi technique identifies proper control factors to obtain the optimum results of the process.

Analysis of S/N ratio

In Taguchi technique, the term ‘signal’ represents the desirable value for the output characteristic and the term ‘noise’ represents the undesirable value for the output characteristic. S/N ratios for different conditions are:

1. Nominal is the best characteristic

$$S / N = 10 \log_{10}\left(\frac{\bar{Y}}{S_y^2}\right) \quad (1)$$

2. Smaller is the best characteristic

$$S / N = - 10 \log_{10}\left(\frac{\sum y^2}{n}\right) \quad (2)$$

3. Larger the better characteristics

$$S / N = -10 \log10\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \quad (3)$$

Where; n is the number experiment performed and y is the output response obtained by the experiment.

Grey relational analysis (GRA)

This technique transforms the multiple performance characteristics into single characteristics. The following steps are followed in GRA

- Experimental data are normalized in the range between zero and one.
- The grey relational coefficients (GRC) are calculated from the normalized experimental data.
- The grey relational grade (GRG) is computed by averaging the weighted GRC corresponding to each performance characteristic.
- Then optimal levels of process parameters are selected.

In the analysis of grey relation for ‘higher is better’ response normalization done by equation (4) and for ‘lower is better’, normalization done by equation (5).

$$X_i^*(k) = \frac{X_i(k) - \dot{X}_i \min(k)}{X_i max(k) - X_i \min(k)} \quad (4)$$

$$X_i^*(k) = \frac{X_i max(\dot{k}) - X_i(k)}{X_i max(k) - X_i \min(k)} \quad (5)$$

Where; Xi*(k) and Xi (k) are the normalized data and observed data, respectively, for i^{th} experiment using K^{th} response.

The smallest and largest values $X_i(k)$ in the K^{th} response are $X_i$min(k) and Xi max(k), respectively.

After pre-processing the data, the grey relation coefficient (GRC) $\zeta_i(k)$ for the K^{th} response characteristics in the i^{th} experiment can be expressed as following:

$$\zeta i\ (k) = \frac{\Delta \min + \zeta\Delta\max}{\Delta i\ (k) + \zeta\Delta\max} \quad (6)$$

Where;

X_0^i (k) = denotes reference sequence , $X^*_j(k)$ = denotes the comparability sequence

ς Є [0,1], is the distinguishing factor; 0.5 is widely accepted.

$\Delta_i = |X_0^*(k)-X_j^*(k)|$ = differnece in absolute value between $X_0^*(k)$ and $X_j^*(k)$

$\Delta_{min}=\min_{(j Є i)}\min_{(k)}|X_0^*(k)-X_j^*(k)|$ = smallest value of$\Delta_{i.}$

$\Delta_{max}=\max_{(j Є i)}\max_{(k)}|X_0^*(k)-X_j^*(k)|$ = largest value of$\Delta_{i.}$

After calculating GRC, the GRG is obtained as:

$$\gamma_i=\left(\frac{\sum w\times \zeta i\ (k)}{m}\right) \quad (7)$$

Where; γ_i is the GRG, n is the number of responses, m is the number of run and w is the weight factor.

Amount of influence of a response can be controlled in deciding the optimum machining parameters varying the value of w keeping in mind $\sum_1^n w$ should be equal to 1.

2.Materials and methods

Scope of AA6061

Aluminium alloy 6061 (AA6061) is one of the most useful aluminium series. Typical properties of AA 6061: medium to high strength, Good toughness and surface finish, excellent corrosion resistance against atmosphere and sea water, good weldability and widely available.

Scope of AA5083

Aluminium alloy 5083 (AA 5083) is known for excellent performance in extreme environments. AA 5083 is highly resistant against seawater and chemical environments. Aluminium alloy 5083 also retains exceptionally good strength after welding. AA 5083 is used in Shipbuilding, Rail cars, Vehicle bodies and Pressure vessels etc.

Chemical composition and mechanical properties of AA 6061 and AA 5083 are given in *Table 1 and 2* respectively.

Table 1 Chemical composition of AA 6061 and AA 5083

AA 6061		AA 5083	
Element	**%Present**	**Element**	**%Present**
Mg	0.8-1.2	Si	Max. 0.4
Mn	Max. 0.15	Fe	Max. 0.4
Cu	0.15-0.40	Cu	Max 0.1
Cr	0.04-0.35	Mn	0.4-1.0
Si	0.4-0.8	Mg	4.0-4.9
Fe	Max. 0.7	Zn	Max. 0.25
Zn	Max. 0.25	Ti	Max. 0.15
Ti	Max 0.15	Cr	0.05-0.25
Al	Balance	Al	Balance

Table 2 Mechanical properties of AA6061 and AA5083

	AA6061	AA5083
Property value	**value**	**value**
Density	2.70 Kg/m^3	2650 Kg/m^3
Young's modulus	68.9 GPA	72 GPa
Tensile strength	124-290 MPa	275 – 350 MPa
Thermal conductivity	151-202 W/(m.K)	121 W/(m.K)

Step-I: 9 pieces of AA 6061 and AA 5083 having 65×60×6 mm dimensions are prepared.

Step II: In welding operation 3 parameters are varied (in 3 levels) as given in *Table 3*.

Table 3 Varied parameters with their levels

Varied parameters	Level 1	Level 2	Level 3
Rotational speed (RS) (rpm)	1200	1400	1600
Transfer speed (TS) (mm/min)	20	30	40
Plunge depth (PD) (mm)	4	4.5	5

From *Table 3*, on the basis of parameters-levels relationship L9 orthogonal array is constructed (presented in *Table 4*) and consequently 9 welding experiments are performed as shown in *Figure 4*. Rockwell hardness and Charpy Impact test was carried out to find out Rockwell hardness on B scale (RHB) and toughness respectively. Values are given in *Table 4*.

Table 4 L9 orthogonal array along with results

S. No.	RS	TS	PD	RHB	Toughness (KSI)
1	1200	20	4.0	24.1	16
2	1200	30	4.5	32.7	36
3	1200	40	5.0	34.1	38
4	1400	20	4.0	29.5	52
5	1400	30	4.5	35.2	46
6	1400	40	5.0	40.6	30
7	1600	20	5.0	41.3	48

S. No.	RS	TS	PD	RHB	Toughness (KSI)
8	1600	30	4.0	44	24
9	1600	40	4.5	44.6	28

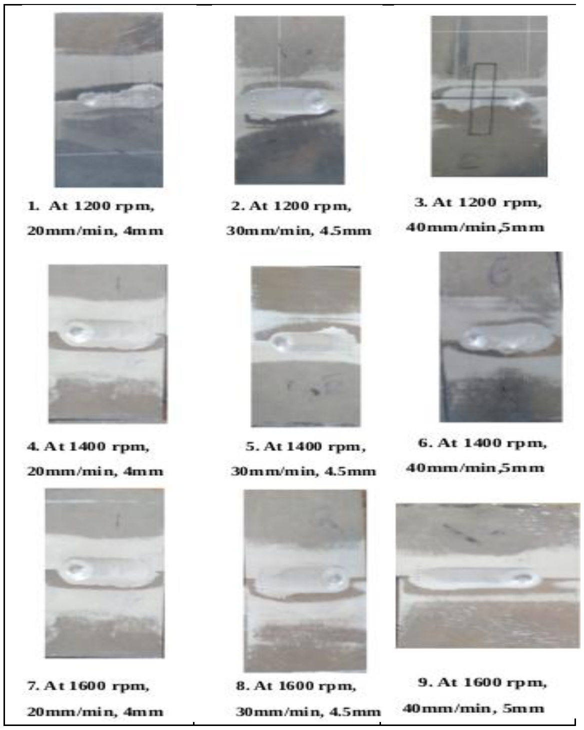

Figure 4 9 Experimental weldments in FSW

3.Results and discussion

From *Table 4*, values are fed in MINITAB software to analyze the main effect of S/N ratios and optimal conditions. *Figure 5* shows the main effect plot for S/N ratios and *Table 5* presents the analysis of variance of hardness.

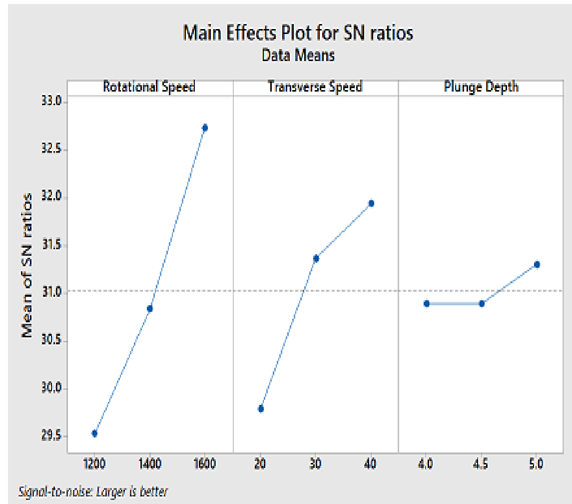

Figure 5 Main effect plot of hardness for S/N ratios

Table 5 ANOVA for hardness

Source	DF	Seq. SS	Contribution
Rotational Speed	2	547.933	80.45%
Transverse Speed	2	105.232	15.45%
Plunge Depth	2	26.726	3.92%
Error	2	1.163	0.17%
Total	8	681.055	100%

In this study lager value of hardness is desirable and higher S/N ratios indicate optimal condition. Therefore optimal process parameters for hardness are evaluated from *Figure 5* and presented in *Table 6*. From *Table 5*, it is also clear that contribution of rotational speed is higher (80.45%) and of plunge depth is lower (3.92%). Error contribution is only 0.17% which vindicates a robust design of experiment.

Table 6 Optimal setting of Process parameters for hardness

Parameter	Levels	Values
RS (rpm)	3	1600
TS (mm/min)	3	40
PD (mm)	3	5

From *Table 6* it can be inferred that all parameters should be high for optimum hardness. Like for hardness, similar analysis is performed for toughness. *Figure 6* shows the main effect plot for S/N ratios and *Table 7* presents the analysis of variance for toughness.

In this study lager value of toughness is desirable and higher S/N ratios indicate optimal condition. Therefore optimal process parameters for toughness are evaluated from *Figure 6* and presented in *Table 8*. From *Table 7*, it is also clear that contribution of plunge depth is higher (54.14%) and of transverse speed is lower (13.62%).

From *Table 8* it can be inferred that plunge depth should be high for optimum toughness while transfer speed should be lower.

Multi response optimization

In order to optimize hardness as well as toughness, multi response optimization i.e. GRA is employed for which GRC and grey relational grades (GRG) are calculated and presented in *Table 9*.

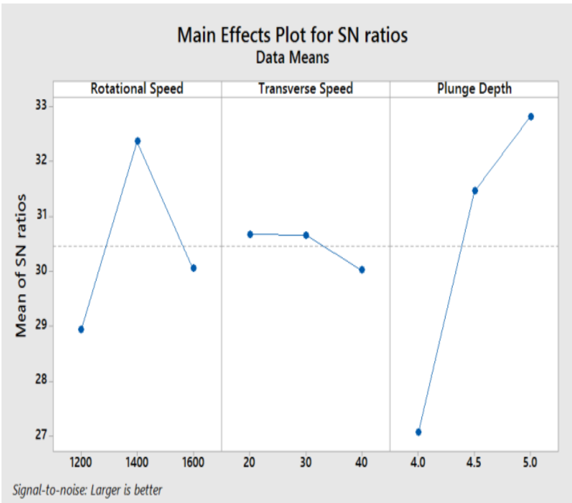

Figure 6 Main effect plot for toughness

Table 7ANOVA for toughness

Source	DF	Seq. SS	Contribution
Rotational speed	2	1343726	23.76%
Transverse speed	2	770030	13.62%
Plunge depth	2	3061614	54.14%
Error	2	479460	8.48%
Total	8	5654830	100.00%

Table 8 Optimal parameter settings for toughness

Parameter	Levels	Values
RS (rpm)	2	1400
TS (mm/min)	1	20
PD (mm)	3	5

Table 9 GRC grades and ranks

Exp. No.	GRC (HRC)	GRC (Toughness)	GRG
1	0.3333	0.3333	0.3333
2	0.4978	0.6157	0.5567
3	0.5340	0.6525	0.5932
4	0.4267	1	0.7133
5	0.5652	0.8276	0.6964
6	0.7660	0.5172	0.6416
7	0.8001	0.8804	0.8402
8	0.9578	0.4325	0.6951
9	1	0.4876	0.7438

GRG from *Table 9* are analyzed in MINTAB for multi response optimization. *Figure 7* shows the main effect plot for S/N ratios and *Table 10* presents the analysis of variance.

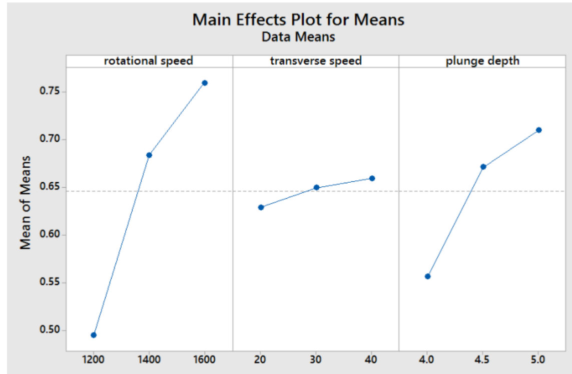

Figure 7 Main effects plot for multi response

Table 10 ANOVA for multi response

Source	DF	Seq. SS	Contribution
Rotational speed	2	0.102272	71.68%
Transverse speed	2	0.002765	1.94%
Plunge depth	2	0.030583	21.44%
Error	2	0.007051	4.94%
Total	8	0.142670	100.00%

Since higher values of hardness and toughness are desired therefore corresponding optimal process parameters for multi response are evaluated from *Figure 7* and presented in *Table 11*. From *Table 10* and *Figure 8*, it is also clear that contribution of rotational speed is higher (71.68%) and of transverse speed is lower (1.94%). Error contribution is only 4.94% which indicates a robust design.

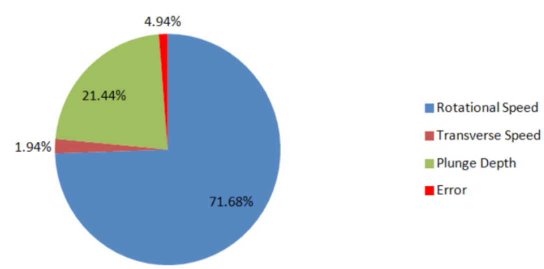

Figure 8 Contribution of parameters in multi response optimization

Table 11 Optimal parameter settings for multiresponse

Parameter	Levels	Values
RS (rpm)	3	1600
TS (mm/min)	3	40
PD (mm)	3	5

From *Table 11*, it can be inferred that for multi responsed optimization i.e. optimization of hardness as well as toughness, rotational speed, transverse speed as well as plunge depth should be higher.

From this study it is conceived that the influence of plunge depth on hardness is insignificant but it is the most effective parameter for toughness. Results also point out that the influence of rotational speed on hardness is very significant but effect is feeble on toughness. In totality to optimize the hardness along with toughness, Multi response optimization suggests that rotational speed is the dominating parameter as compare to plunge depth.

4.Conclusion and future work

In optimization of hardness of the welding joint, contribution of rotational speed is higher and all parameters should be high. In optimization of toughness, contribution of plunge depth is higher. It is also observed that transfer speed should be lower. In multi response optimization i.e. optimization of hardness as well as toughness contribution of rotational speed is higher and all parameters should be high.

In future, this experiment can be designed on the basis of 4 parameters (including coolants) and 4 levels to construct L16 orthogonal array. Also there is scope to analyze the bending strength along with hardness and toughness in multi response optimization.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

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