Multi-Objective Optimization of Joint Strength of Dissimilar Aluminum Alloys Formed by Friction Stir Welding Using Taguchi-Grey Relation Analysis

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Abstract-- **Friction Stir Welding (FSW) is a solid state joining process which eliminates the drawbacks of conventional fusion welding and hence associated pollution. The present study is intended to improve the process parameters of Friction Stir Welding (FSW) for joining two dissimilar aluminum alloys (AA7075 and AA6061). Multi-objective optimization of control factors (thickness of plate, axial load, tool rotational speed, welding speed and tilt angle) was carried out using a hybrid Taguchi-Grey approach to evaluate the quality characteristics such as tensile strength, impact strength and percentage of tensile elongation. The experiment was carried out by using Taguchi based mix level design L18 orthogonal array. The Grey grade corresponding to each quality characteristic is determined so that their influence can be properly explained. Analysis of Variance (ANOVA) is also used to ascertain the effect of each parameter on output characteristics of FSW process. The conduction of confirmation tests verified the optimal conditions.**

Index Term-- **Orthogonal Tables (OA), Taguchi Method, Grey Relational Analysis (GRA), Aluminum Alloys, Yield Strength, Impact Strength, Multi-Response Optimization, FSW, ANOVA, Verification Tests.**

1. INTRODUCTION

Need of present advancement in science and technology is to produce stronger joints than fusion welding (using filler material) using processes involved to be fast, efficient, environmental friendly and providing higher mechanical properties such as impact strength, hardness, elongation and tensile strength, etc. Friction stir welding (FSW) is an alternate to the conventional welding method and free from welding defects such as porosity, oxidation and other defects of the conventional fusion welding processes [1-3]. FSW most useful joining technique has extensive applications in aerospace, automotive and shipbuilding industries especially, aluminium, titanium, and magnesium which are lightweight materials [4]. In 1991, The Welding Institute (TWI), UK, introduced a basic concept of using the non-consumable rotating tool (consisting of pin and shoulder) and inserting into the butting edges of plates. First time, it was performed on Aluminium and its alloys, but now, it can be successfully applied on titanium, magnesium, copper, and different material combinations with the help of the tool as a third member for joining two butted faces of similar or dissimilar metals [5]. It has an advantage of a soft region between the metal surfaces and tool due to heat generation. FSW process can be used in producing butt, corner, lap, T, spot, fillet, hem joints, hollow objects such as tanks, tubes, pipes, stocks, of different thicknesses, tapered sections, and even 3D contoured parts [1]. Investigations on the effect of process parameters of FSW namely, tool rotational speed, welding table speed, tilt angle, plate thickness and axial force on weldment quality has become a central area for researchers [6-8]. Previously, most of the researchers followed the conventional experimental techniques to study the effect of FSW process parameters by varying one output at a time, and this design of experiment (DOE) approach is time consuming. For producing a high quality welded joint, it is necessary to optimize the process parameters for multi-outputs. There are various approaches to carry out optimization for producing the high quality welded joint such as Taguchi design method, response surface, and grey relation analysis, etc. Some of the researchers applied response surface methodology successfully to conduct parametric studies of joining different materials by FSW [1].

The Taguchi method is powerful statistical DOE tool to perform an optimization for improving the quality of product/process at a low cost allowing one output at a time [6]. In the case of multi-objective optimization, Taguchi method is difficult to use while knowing which factor plays an important role in any process having multi-outputs compared to single output optimization [9]. The relationship between welding speeds and process factors in FSW of an Aluminium Alloy and the heat input during welding is complicated. AA5083 alloy gave multiple responses based on the increasing the rotation speed or orthogonal array size using grey relational approach. It is also noticed that the decrease in the welding speed could result in a high-temperature weld. In FSW, an extensive plastic flow of material is required to minimize the forces acting upon the tool and used in optimizing the FSW process for the tensile strength of the welds [10, 11].

Multi-output optimization of the FSW process for an optimal parametric combination using the Taguchi based Grey relational analysis found that process parameters are tool rotating speed, the welding speed of table and tool shoulder diameter were important during the experiments using Taguchi L8 orthogonal array [12]. In the present work, an attempt has been made to carry out the experiments based on the L18 orthogonal array to overcome difficulties experienced by previous researchers and to handle more process parameters for obtaining a quality weld using Taguchi based grey relation analysis.

Most of the present research focuses on similar aluminium sheets FSW and a little work carried on dissimilar FSW using only aluminium alloys of different grades [13]. To set up an experimental design procedure for dissimilar FSW a systematic approach on parameters optimization requires multi-output optimization using Taguchi based Grey relational analysis followed by ANOVA and verification test are used to ascertain the most influential parameters and predict the best combination of parameters to yield the optimum quality. Only a few of similar metals FSW of RDE-40 aluminium alloy and 5086 aluminium plates have successfully analysed using Taguchi method [1, 12, 14]. In the case of dissimilar metals AA2219-AA5083 dissimilar FSW using only Taguchi method considering few parameters, one output without ANOVA and confirmation test carried out to optimize the parameters. Some researchers also tried to solve the problem of multiple quality characteristics by the Taguchi design method but not by using Taguchi based grey relation analysis (GRA) [15].

2. GREY RELATIONAL ANALYSIS

In 1982, GRA proposed by Deng *et.al.*, to handle the basic mathematical criteria for dealing with a poor, incomplete, and conditional system [16]. Later on, Taguchi based grey relation analysis approach helped in transforming all responses into one index is known as grey relation grade. Optimization of FSW process parameters of AA5083 aluminium alloy with multiple responses based on Taguchi orthogonal array (OA) of DOE with grey relation analysis and found that tool rotational speed is most significant process parameters [17, 18]. The author in [19] used the Taguchi method for dissimilar AA6082 and AA7075 aluminium alloys and observed that welding speed is a highly important process parameter.

The study on the effect of FSW process parameters of dissimilar FSW of AA6061 - AA7075, most of the researchers followed the conventional experimental techniques, in which varying one parameter at a time while other parameters are constant. This classic parametric design of experiment approach is time-consuming. The Taguchi based grey method will be applied to predict the optimum parameters and subsequently produce a weld joint with the highest mechanical properties.

Therefore, in this work, we have performed the Taguchi based GRA method to optimize the process parameters of FSW for dissimilar base metals (AA6061 and AA7075) and to produce strong FSW joint. Morover, the FSW process parameter on multiple outputs such as impact strength, tensile strength, and tensile elongation are considered as the quality characteristics. Indeed, the GRA is very useful while applying to a system having less or incomplete information. Figure 1 shows the steps are involved in GRA methodology.

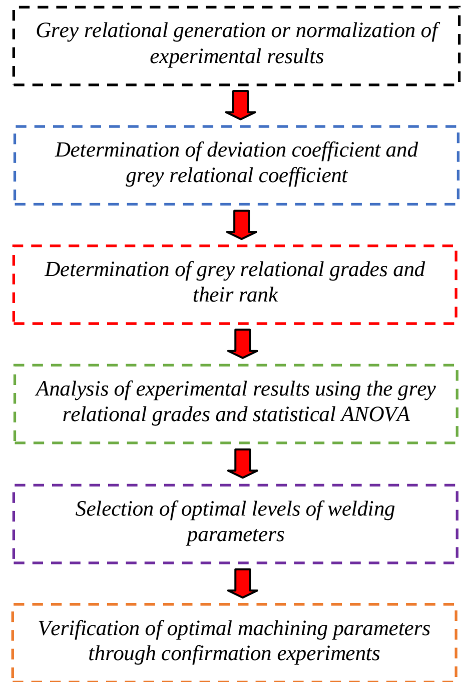

Fig. 1. Steps involved in GRA methodology

3. EXPERIMENTAL METHODOLOGY

In the present work, dissimilar aluminium alloys namely, AA 7075 and AA6061 with varying thicknesses of 3 and 4 mm whose chemical composition is listed in Table I. Welding was carried out in butt joint configuration using vertical milling machine with a special tool as shown in Figures 2 and 3. From the literature, it has been considered the process parameters that have a greater influence on mechanical properties are axial force tool rotational speed, welding speed, tilt angle, and plate thickness are summarized in Table II. To avoid these problems design of experiment based Taguchi method can be used for reducing the number of experiments. Butt welded samples were prepared using vertical milling machine with a rig used consisting of mild steel backing plate to along the rolling direction mild steel backing plate to support for base metal during FSW process. A tool with cylindrical taper profile having pin diameter 6 mm and 10° taper, pin length 1.8 mm, and shoulder diameter of 20 mm was chosen for welding. To get better material mixing, plates are to welded by placing on the advancing side and retreating side alternatively.

TABLE I
Chemical composition of base metal aluminum alloys (AA6061 and AA7075)

Material	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Al
AA6061	0.550	0.40	0.25	0.535	0.85	0.007	0.20	0.030	97.178
AA7075	0.075	0.28	1.60	0.019	2.30	5.600	0.22	0.028	89.878

Fig. 2. Joining of alloys by FSW process

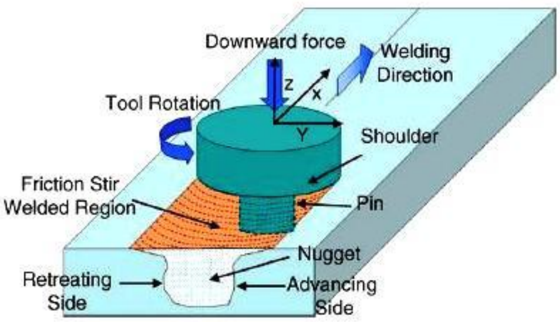

Fig. 3. Schematic drawing of FSW process, adapted from [2]

TABLE II
Process parameters and friction stir welding levels

Factor	Parameter	Level 1	Level 2	Level 3
A	Thickness of plate (mm)	3	4	--
B	Axial load (KN)	2	2.5	3
C	Rotational speed (rpm)	600	900	1200
D	Welding speed (mm/min)	75	90	115
E	Tilt angle (degrees)	3	4	5

In the Grey Relational method, the experimental data are initially normalized in the range of zero to one and this data pre-processing is called Grey relation generation. The normalization is computed based on quality characteristics such as "*the-smaller-the-better*" and "*the-larger-the-better*" using Equations (1) and (2), respectively. Thereby, original sequences will be changed into a set of corresponding sequences during this step. In the present study, Taguchi-based GRA is used to optimize welding characteristics of FSW process parameters for multiple output quality features such as yield strength, % of elongation, impact strength (Joules/mm^2) to get a better quality welded joint depending on the quality characteristics of the experimental data. The initial sequence (reference sequence) and pre-processed data are represented by y_i^* (p) and y_i^0 (p), i =1, 2, (p) and (p), i = 1, 2, …, a; p = 1, 2, ..., b; respectively, where a and b are the number of experiments and observations of data respectively. If the initial sequence data has the quality characteristic of "lower-*the-better*" in the GRA, first of all, the results or responses are normalized using Equations (1) for the experimental data plan [21].

- Lower-is-the-better (LB):

$$y_i^*(p) = \frac{\max y_i^0(p) - y_i^0(p)}{\max y_i^0(p) - \min y_i^0(p)} \quad (1)$$

- Higher-is-the-better (HB):

$$y_i^*(p) = \frac{y_i^0(p) - \min y_i^0(p)}{\max y_i^0(p) - \min y_i^0(p)} \quad (2)$$

where, $y_i^*(p)$ is the sequence after the data processing or compatibility sequence, $y_i^0(p)$ is the original sequence of the target value. For the present analysis, a = 16 and b = 2. The next step is to determine the deviation coefficient, which is the absolute value of the difference between the reference sequence and compatibility sequence, i.e.

$$\Delta_i^o(p) = y_o^*(p) - y_i^*(p) \quad (3)$$

where, $\Delta_i^o(p)$ is the deviation coefficient, $y_o^*(p)$is the reference or ideal sequence. The Grey relational coefficient is then determined using Equation (3):

$$\gamma = \left(y_0^*(p) \times y_i^*(p)\right) = \frac{\Delta_{min} + \varsigma \cdot \Delta_{max}}{\Delta_i^o(p) + \varsigma \cdot \Delta_{max}} \quad (4)$$

where, $\left(y_0^*(p) \times y_i^*(p)\right)$ is the Grey relational coefficient and is the distinguishing coefficient (0 - 1). Here we selected ζ = 0.5. The Grey relational grade $\gamma(y_o^* \cdot y_i^*)$ is the weighted sum of the ζ Grey relational coefficients and represents the level of correlation between reference and compatibility sequence. It can be calculated using Equation (5):

$$\gamma(y_0^* \cdot y_i^*) = \frac{1}{N}\gamma\left(y_0^*(p) \cdot \gamma\left(y_i^*(p)\right)\right) \quad (5)$$

The Grey relational grades are then sequenced in descending order, because the higher value of the grey relational grade represents the stronger relational degree between the reference and compatibility sequence. The highest value of Grey relational grade represent the optimal combination of control parameters for the desired responses.

4. MULTI-RESPONSE OPTIMIZATION OF PROCESS PARAMETERS

Taguchi's L18 orthogonal array DOE consisting of 18 sets of data was selected to optimise the mix level process parameters used in the multiple welding characteristics of the FSW performance of dissimilar aluminium alloys to produce better quality. Experiments were conducted with the L18 layout of control factors and normalised data of mechanical properties as shown in Table III and Table IV. The target values of these are "*larger-is-the-better*" used in the Grey analysis and evaluation of the optimal combination of process factors [15].

Grey relation generation was done by using Equation (2) for normalizing the experimental results, sequence deviations were determined from Equation (3) and the distinguishing coefficients in Equation (4) using the above sequences deviation. Grey Relational Coefficients (GRC) are evaluated using Equation (4). Deviation and Grey relational coefficients are tabulated in Table V. Then, GRCs are to be averaged using equal weighting to obtain the Grey relational grade using Equation (5) [22]. We used an OA of the Taguchi method to obtain the mean Grey relational grades for each parameter level as shown in Table VI. Grey relational grades represent the index of correlation between the reference and the comparability sequences. Therefore, the higher value of GRA grade is selected[6]. GRA was applied to find the most significant parameter based on the combination of the levels which provides the largest average response and which is the optimal factor combination for the FSW.

Grey relational grades and their rank for the multiple mechanical properties of FSW are shown in Table VI. The higher grade Grey relational will have better multi-output welding characteristics. We can see that Grey relational grade order shows that experiment number 6 has the best optimal setting. Mean response tables were generated using Taguchi design method for quality characteristic as "*higher-the-better*" to calculate the mean Grey relational grade for each parameter level along with difference Δ and rank of each control factor with respect to Δ as shown in Table VII.

Table VII shows that the highest values of Grey relational grade are obtained by the combination of P2-L3-R3-W3-T1. This represents the optimal combination of FSW control parameters for the multiple outputs of welding characteristics during estimation of quality of joint. P2-L3-R3-W3-T1 combination shows a thickness of plate of 4 mm, an axial Load of 3KN, rotational Speed of 1200 rpm, welding speed of 115 mm/min and tilt angle of 3°. The main effect plots for means of Grey relational grade of various process parameters are shown in Figure 4. The dashed lines represent the total mean of the Grey relational grade in the graph. It also shows how the various residual plots of Grey relational grade are evaluated to understand the effectiveness of technique applied in an optimization.

TABLE III
Experimental results of welding characteristics of FSW process

No.	**Thickness of Plate**	**Axial Load**	**Rotational Speed (rpm)**	**Welding Speed (mm/min)**	**Tilt Angle**	**Yield Strength**	**% of Elongation**	**Impact Strength (Joules/mm²)**
1	3	2.0	600	75	3	200	7.3	0.91
2	3	2.5	600	90	4	210	8.1	0.63
3	3	3.0	600	115	5	215	8.5	0.69
4	3	2.0	900	75	4	208	8	0.54
5	3	2.5	900	90	5	219	8.9	0.72
6	3	3.0	900	115	3	250	11.4	0.55
7	3	2.0	1200	90	3	220	9	0.65
8	3	2.5	1200	115	4	204	7.4	0.80
9	3	3.0	1200	75	5	216	7.8	0.58
10	4	2.0	600	115	5	214	9	0.82
11	4	2.5	600	75	3	208	8.7	0.76
12	4	3.0	600	90	4	218	9.6	0.7
13	4	2.0	900	90	5	230	9.2	0.75
14	4	2.5	900	115	3	220	9.4	0.67
15	4	3.0	900	75	4	225	10.5	0.73
16	4	2.0	1200	115	4	210	12	0.78
17	4	2.5	1200	75	5	204	11	0.84
18	4	3.0	1200	90	3	206	12.5	0.71

TABLE IV
Data preprocessing of welding characteristics of FSW process

Run no.	***FSW Control Factors***					***Experimental Results***			***Normalized Data***		
	Thickness of Plate	**Axial Load**	**Rotational Speed**	**Welding Speed**	**Tilt Angle**	**Yield Strength (MPa)**	**% of Elongation**	**Impact Strength (Joules/mm^2)**	**Yield Strength (MPa)**	**% of Elongation**	**Impact Strength (Joules/mm^2)**
Ideal Sequence									1	1	1
1	3	2.0	600	75	3	200	7.3	0.91	0	0	1
2	3	2.5	600	90	4	210	8.1	0.63	0.2	0.15384615	0.243243243
3	3	3.0	600	115	5	215	8.5	0.69	0.3	0.23076923	0.405405405
4	3	2.0	900	75	4	208	8	0.54	0.16	0.13461538	0
5	3	2.5	900	90	5	219	8.9	0.72	0.38	0.30769231	0.486486486
6	3	3.0	900	115	3	250	11.4	0.55	1	0.78846154	0.027027027
7	3	2.0	1200	90	3	220	9	0.65	0.4	0.32692308	0.297297297
8	3	2.5	1200	115	4	204	7.4	0.80	0.08	0.01923077	0.702702703
9	3	3.0	1200	75	5	216	7.8	0.58	0.32	0.09615385	0.108108108
10	4	2.0	600	115	5	214	9	0.82	0.28	0.32692308	0.756756757
11	4	2.5	600	75	3	208	8.7	0.76	0.16	0.26923077	0.594594595
12	4	3.0	600	90	4	218	9.6	0.7	0.36	0.44230769	0.432432432
13	4	2.0	900	90	5	230	9.2	0.75	0.6	0.36538462	0.567567568
14	4	2.5	900	115	3	220	9.4	0.67	0.4	0.40384615	0.162162162
15	4	3.0	900	75	4	225	10.5	0.73	0.5	0.61538462	0.513513514
16	4	2.0	1200	115	4	210	12	0.78	0.2	0.90384615	0.648648649
17	4	2.5	1200	75	5	204	11	0.84	0.08	0.71153846	0.810810811
18	4	3.0	1200	90	3	206	12.5	0.71	0.12	1	0.459459459

TABLE V
Deviation and Grey relational coefficients of welding characteristics of FSW process

Run No.	***Deviation Coefficient***			***Grey Relational Coefficient***		
	Yield Strength	**% of Elongation**	**Impact Strength**	**Yield Strength**	**% of Elongation**	**Impact Strength**
Ideal Sequence				1	1	1
1	1	1	0	0.333333	0.333333333	1
2	0.80	0.84615385	0.75675676	0.384615	0.371428571	0.397849
3	0.70	0.76923077	0.59459459	0.416667	0.393939394	0.456790
4	0.84	0.86538462	1	0.373134	0.366197183	0.333333
5	0.62	0.69230769	0.51351351	0.446429	0.419354839	0.493333
6	0.00	0.21153846	0.97297297	1	0.702702703	0.339450
7	0.60	0.67307692	0.70270270	0.454545	0.426229508	0.415730
8	0.92	0.98076923	0.29729730	0.352113	0.337662338	0.627119
9	0.68	0.90384615	0.89189189	0.423729	0.356164384	0.359223
10	0.72	0.67307692	0.24324324	0.409836	0.426229508	0.672727
11	0.84	0.73076923	0.40540541	0.373134	0.406250000	0.552239
12	0.64	0.55769231	0.56756757	0.438596	0.472727273	0.468354
13	0.40	0.63461538	0.43243243	0.555556	0.440677966	0.536232
14	0.60	0.59615385	0.83783784	0.454545	0.456140351	0.373737
15	0.50	0.38461538	0.48648649	0.500000	0.565217391	0.506849
16	0.80	0.09615385	0.35135135	0.384615	0.838709677	0.587302
17	0.92	0.28846154	0.18918919	0.352113	0.634146341	0.725490
18	0.88	0	0.54054054	0.362319	1	0.480519

TABLE VI
Grey relational grades and their order

Run No.	Grey Grade	Order
1	0.555556	5
2	0.384631	16
3	0.422465	15
4	0.357555	18
5	0.453039	10
6	0.680717	1
7	0.432168	13
8	0.438965	12
9	0.379705	17
10	0.502931	8
11	0.443874	11
12	0.459893	9
13	0.510822	7
14	0.428141	14
15	0.524022	6
16	0.603542	3
17	0.570583	4
18	0.614279	2

TABLE VII
Response table for means of Grey relational grade

Process Parameters	Grey Relational Grade (GRG)			Delta = $GRG_{(Max)}$ - $GRG_{(Min)}$	Rank
	Level 1	Level 2	Level 3		
Thickness of Plate (P)	0.4561	0.5176	--	0.0615	2
Axial Load (L)	0.4938	0.4532	0.5135	0.0603	3
Rotational Speed (R)	0.4616	0.4924	0.5065	0.0450	4
Welding Speed (W)	0.4719	0.4758	0.5128	0.0409	5
Tilt Angle (T)	0.5258	0.4614	0.4733	0.0644	1
Total mean Grey relational grade = 0.454					

Fig. 4. Plot of total mean of Grey relational grade *vs.* control factors

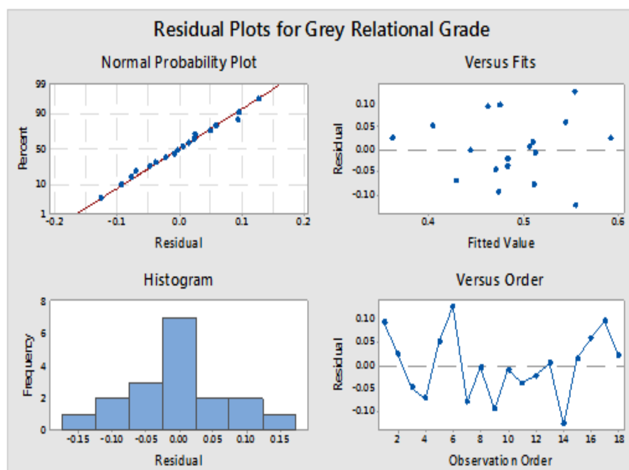

Fig. 5. Residual plots of Grey relational grade

5. ANOVA ANALYSIS

ANOVA is used to find the most/major significant parameter which affects the output quality and characteristic using the quantities such as degree of freedom (DOF), sum of squares (SS), variance (V), and how the percent contribution of each parameter *F*-ratio and *P*-values are determined. The ANOVA method has been applied to determine the GRA grades/ranks at 95% confidence level for investigating the most and least significant level of process factors on multiple welding characteristics of FSW of dissimilar aluminum alloys.

Fisher's value, *F*, and probability of significance, *P*, can be used to determine an importance of welding characteristic control factors on the multiple mechanical properties. For a large value of *F* (or small value of *P*), the corresponding parameter has a significant effect on the performance characteristics. The percentage of contribution of a parameter can be calculated by dividing SS by the corresponding SS. A residual plots for the Grey relational grade are shown in Figure 5.

Table VIII represents the fact that thickness of plate is the major significant process parameter for mechanical properties considered simultaneously for the multi-response characters of FSW and is 59.82%. A regression Equation (6), regression equation, is also obtained to provide a mathematical model involving process parameters:

$$\text{Grey Relational Grade} = 0.4868 - (0.0307\times P_1) + (0.0307\times P_2) + (0.0069\times L_1) - (0.0336\times L_2) + (0.0267\times L_3) - (0.0253\times R_1) + (0.00568\times R_2) + (0.0197\times R_3) - (0.0149\times W_1) - (0.0110\times W_2) + (0.0260\times W_3) + (0.0390\times T_1) - (0.0254\times T_2) - (0.0136\times T_3) \quad (6)$$

TABLE VIII
ANOVA for Grey relational grade

Parameters	DF	SS	Adj MS	F	P	Contribution Ratio
Thickness of Plate	1	0.0170070	0.017007	1.66	0.233	59.82
Axial Load	2	0.0081729	0.005672	0.31	0.741	8.3
Rotational Speed	2	0.0140820	0.010216	0.69	0.529	12.44
Welding Speed	2	0.0061140	0.003057	0.30	0.749	4.475
Tilt Angle	2	0.0113440	0.007041	0.56	0.595	10.3
Error	8	0.0063480	0.003174	--	--	4.65
Total	17	0.1366240	--	--	--	100.00

6. FSW VERIFICATION

The optimal set of parameters combination for achieving maximum yield strength is % of elongation and is obtained using Taguchi-based GRA as P2-L3-R3-W3-T1. Moreover, a confirmation test is carried out by using P2-L3-R3-W3-T1 optimal setting. The results of the verification test were impact strength of 0.82 Joules/mm^2, tensile strength of 226 N/mm^2 and % of elongation 9.5. The confirmation test result obtained exhibited better than the experimental results in Table III. After finding the optimal combination of welding characteristics control parameters and the most influential factor, the final step was to verify the feasibility of the proposed combined Taguchi-based GRA by conducting some confirmation tests. Table IX shows the results of the confirmation tests. The optimum Grey relational grade, Γ_{opt}, is calculated as [23].

TABLE IX
Welding performance results using the initial and optimal process parameters

Level	Initial Parameters	Optimal Parameters	
		Prediction	Experiment
	P1-L3-R2-W3-T2	P2-L3-R3-W3-T1	P2-L3-R3-W3-T1
Tensile Strength	215	--	226
% of Elongation	8.0	--	9.5
Impact Strength	0.75	--	0.82
Grey Relational Grade	0.59	0.629	0.65

$$\Gamma_{opt} = \Gamma_m + \sum_{i=1}^{q} (\Gamma_i - \Gamma_m) \quad (7)$$

where, Γ_m and Γ_i, are the total mean of the Grey relational grade and the mean of the Grey relational grade of i^{th} parameter at the optimal level respectively, and *q* is the number of most influential of process parameters.

In the above three cases, the values of mechanical properties of an optimal combination of process parameters were sufficiently higher as compared to those of initial process parameters. The improvements in Grey relational grade for optimal parametric combination than that for initial process parameters are 0.75868. Three additional experiments are performed with levels at optimal parameter settings and the average of those three results is taken for the confirmation test. Indeed, Table 8 furnishes the predicted value of Grey relation grade and the result of the confirmation test. It is found that welding characteristics of FSW viz. tensile strength improved from 215 to 226, % of elongation improved from 8.0 to 9.5 and impact strength improved from 0.75 to 0.82.

7. CONCLUSION

The Taguchi-based Grey Relation Analysis approach was applied in the present research to optimize the control factors of response characteristics of FSW process for joining two dissimilar aluminum alloys. The following concluding remarks summarize the results:

- The numerical values of the Grey relational grade quantify the integrated performance of FSW process factors used in weldable characteristics required in high mechanical properties of joints.
- From the average response table, the highest value of the Grey relational grade is achieved for the thickness of plate of 4 mm, axial load of 3.0 KN, rotational speed of tool of 1200 rpm, welding speed of 115 rpm and tilt angle of 3° for FSW characteristics of joining two dissimilar aluminum alloys. These could be recommended levels of FSW process parameters for high-properties requirements considered in various industries.

- Results of ANOVA for the Grey relational analysis grade showed that the thickness of plate is the sole most significant welding characteristic control factor for the multi-output characteristics under consideration. The contribution of thickness of plate is quite large 52.82% as compared to the other control factors of commercially available FSW welding in the aerospace industry.
- Confirmation tests/experiments disclosed that the improvement in Grey relational grade of an optimal combination of parameters 0.629 compared to an initial setting of parameters 0.59.

Therefore, the GRA based on Taguchi design method can be applied to an optimization of control factors of multi-output performance and also helps in improving the efficiency of a process.

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