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To cite this article: K Palani and C Elanchezhian 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **390** 012061

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Multi response Optimization of Friction stir welding process parameters in dissimilar alloys using Grey relational analysis

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Abstract. A multi response optimization of friction stir welding parameters in dissimilar alloys using Taguchi based Grey relational analysis was studied in this investigation. The dissimilar nonferrous AA8011-H24 aluminium alloys and Ti3Al2.5V titanium alloys were friction stir welded under different process parameters, viz., rotational speed, tool pin profiles and welding speed on tensile strength, tensile elongation and joint efficiency have been optimized by applying multi response analysis. The grey relational grade is attained which correlates between the friction stir welding parameters and responses and the optimum level of welding parameters have been determined by grey analysis. The rotational speed is the most significant contributing parameter to decide the good quality of the welded joints followed welding speed and the tool pin profiles was found using analysis of variance. The confirmation test results showed that the grey relational grade was improved 0.059 with the predicted responses at the optimal conditions.

1. Introduction

The focus on dissimilar joining of aluminum and titanium alloys is considered in the potential application between low and high melting alloys in the field of aerospace and automobile industry, which has the unique properties of high strength to weight ratio, corrosion resistance, reduction of weight and cost (due to Al alloy) and improve strength (due to Ti alloy). The great challenge of the joining of aluminum and titanium alloys due to the different properties mainly, melting temperature and coefficient of heat transfer coefficient is considered in material joining industries [1]. Due to the temperature variation in melting and solidifying the metals in the fusion welding process, the brittle intermetallic compounds are formed at the interface of the dissimilar Aluminium and Titanium joints which deteriorates the strength of the welded joints [2, 3]. The conventional fusion welding process such as metal inert gas welding [4], tungsten inert gas welding [5] and laser welding [6] is carried out on the dissimilar materials. The other solid state joining processes viz., diffusion bonding [7, 8] and friction welding [9] for joining of titanium and aluminium alloys have been investigated. The newly invented solid state joining technique, The Friction stir welding (FSW) process is applied in joining of dissimilar materials to overcome the problems such as solidification shrinkage, hot cracking, improper fusion, porosity and loss of work hardening which occurred in the fusion welding process [10]. This process was initially applied to the similar aluminium alloys and developed by The Welding Institute (TWI), Cambridge in 1991 [11].

The micro structural evolution was examined in the friction stir welding (FSW) of dissimilar materials with the parameters of rotational speed, transverse speed, plunge depth, tool tilt angle, diameter ration of tool shoulder and tool pin and various pin shapes [12] effectively. Thereby the selection of FSW parameters is very critical to decide the quality of the welded joints for the dissimilar materials. The multi objective optimization techniques are used to optimize the responses of the FSW process with suitable process variables of dissimilar materials. For instance, Shanmuga Sundaram N et al. [13] successfully welded the hot worked AA2024 aluminium alloy with the cold worked AA5083 aluminium alloy with five different tool pin profiles using the friction stir welding. They developed the



mathematical models which give the good correlation between the process parameters and the responses of the friction stir butt welded joints. They examined that the highest tensile elongation and tensile strength of the joints was found in tapered hexagon pin profile due to its higher pulsating effect and smooth material flow, whereas the straight cylinder pin profile gave the lower strength and elongation of the joints. Palani et al [14] discussed the effect of the friction stir welding process parameters of the AA 8011 aluminium alloys and successfully optimized the parameters using the response surface methodology. They examined that the higher relative efficiency decides the quality of the welded joints. Ghosh M et al. [15] successfully optimized the friction stir welding process parameters of the dissimilar aluminium alloys and found that due to the zone of Si rich particles in the retreating side, the interface microstructure occurred within the stir zone of the welded joints. They reported that the lower tool rotational speed and traverse speed gave the fine equiaxed grains near the AA6061 alloy interface due to proper material intermixing and dynamic crystallization of the materials.

Vijayan et al. [16] optimized the FSW process parameters of AA5083 aluminum alloy with multiple responses with grey analysis. They found that the maximum tensile strength and minimum power of the FSW joints based on the optimum levels of the process parameters welded joints. Palani et al [17] successfully applied the Taguchi method for the optimization of multiple responses of the friction stir welded AA8011 aluminium alloys. They reported the highest signal to noise ratio was the key factor to decide the quality of the welded joints. Kasman [18] optimized the multiple responses for the dissimilar FSW process of AA6082-AA5754 aluminum alloys successfully by Taguchi based grey analysis. In the present investigation, the attempt has been carried out on the multi response optimization of friction stir welding process parameters in dissimilar non-ferrous alloys of Ti3Al2.5V titanium alloy and AA8011 aluminium alloy using Taguchi based grey relational analysis.

2. Grey relational analysis

The quality of the welded joints is decided by the proper selection of parameters of the friction stir welding process. The optimum settings of process parameters are mainly focused to enhance the properties of the joints using different statistical approaches. In this work, the Taguchi method was applied to conduct the experiments based on L_{27} orthogonal array design and to improve the fabricated joint properties of the welded joints using friction stir welding process on two dissimilar non-ferrous alloys. The objective of the work is to optimize the friction stir welding parameters on the multiple responses such as, tensile strength, tensile elongation and joint efficiency. The multiple responses of the dissimilar friction stir welding process have considered as the higher-the-better- performance characteristics using the Taguchi method. The Grey relational analysis was applied to improve the all the response characteristics without degrading the performance of the joints [19]. The following steps are considered to find the optimum responses based on the grey relational grade using Taguchi based grey relational analysis.

2.1 Normalization of the responses

In the grey relational analysis, data preprocessing was initially made in order to normalize the experimental data and the linear normalization of the signal to noise ratio was attained in the range between 0 and 1 for further analysis [20]. In this study, the larger-the-better characteristic was considered for the responses of the dissimilar friction stir welding, such as tensile strength, tensile elongation and joint efficiency and these can be expressed as follows:

$$x_{ij} = \frac{\eta_{ij} - \min_j \eta_{ij}}{\max_j \eta_{ij} - \min_j \eta_{ij}} \quad (1)$$

Where, η_{ij} is the original sequence for the i^{th} response in the j^{th} experiment, and x_{ij} is the normalized value of the i^{th} response in the j^{th} experiment. The normalized response is closer to one which gives the best experimental results according to Deng grey rule [21].

2.2 Calculation of Grey relational Coefficient

After normalizing the responses, the grey relational coefficient was determined to give the relationship between the best and actual normalized responses and can be expressed as:

$$\xi_{ij} = \frac{\Delta \min_j + \zeta \Delta \max_j}{\Delta_{oij} + \zeta \Delta \max_j} \quad (2)$$

Where, Δ_{oij} is the normalized response to the i^{th} response in the j^{th} experiment and ζ is the distinguishing coefficient, which is considered as 0.5 for the analysis. The table 3 shows the grey relational coefficient for each response characteristic.

2.3 Determination of Grey relational grade

The average grey relational grade was computed for the each response of the friction stir welding process and expressed as:

$$\alpha_j = \frac{1}{n} \sum_{i=1}^n \xi_{ij} \quad (3)$$

Where, n is the number of responses and α_j is the grey relational grade for all the responses of the welded joints. The experiment 7 shows the highest grey relational grade, which is closer to the ideally normalized response.

3. Experimental work

The titanium alloy Ti3Al2.5V alloy and AA8011 aluminium alloy [22] (Procured from Kataria Steels, Mumbai) were used in this investigation with the dimensions of 100 mm x 100 mm x 6 mm and used for butt joint configuration using friction stir welding process. The chemical composition of the AA8011 aluminium alloy and Ti3Al2.5V titanium alloy are presented in Table 1. The plates for investigation initially washed with an ultrasonic bath sonicator and the butt surfaces were cleaned with acetone. The dissimilar butt welding was carried out using Computerized Friction stir welding machine (Fabricated by Universal Industries, Model AMS 400S, Kanchipuram) shown in Figure 1 and the welding operations was performed by clamping the plates properly with the fixture.

Table 1. Chemical composition of the AA8011-H24 Aluminium alloy and Ti3Al2.5V Titanium alloy

Chemical composition (Wt.%) of Aluminium alloy (AA8011-H24)				
Fe – 0.74%	Si – 0.56%	Mn – 0.10	Mg – 0.08	Cu – 0.13
Zn – 0.08	Cr – 0.10%	Ti – 0.05	Remaining Al	
Chemical composition (Wt.%) of Titanium alloy (Ti3Al2.5V)				
Fe – 0.30%	Si – 0.14%	Al – 2.9%	V – 2.5%	O – 0.15%
C – 0.05%	H – 0.02%	N – 0.02%	Remaining Ti	

The newly fabricated friction stir welding tools made of M2 tool steel (Manufactured by SRS Diamond tools, Chennai) with the dimensions of 18 mm shoulder diameter, 6 mm pin diameter and 5.7 mm pin length were used to produce the friction butt welded joints. The three different tool pin profiles, namely Straight Square, Straight Pentagon and Straight Hexagon pin profiles were used to make the butt welded joints of dissimilar alloys shown in Figure 2. The quality of the weld was decided by proper selection of process parameters of the friction stir welding process.

Table 2. Friction stir welding parameters and their levels

Control process parameters	Unit	Symbol	Levels		
			1	2	3
Rotational Speed	r/min	A	300	350	400
Tool pin profile	---	B	1 (Square)	2 (Pentagon)	3 (Hexagon)
Welding Speed	mm/min	C	30	35	40

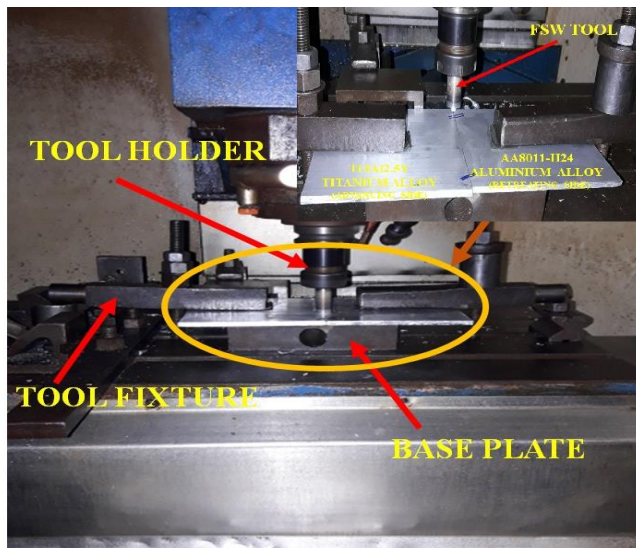


Figure 1. Friction stir welding (FSW) machine



Figure 2. FSW tool pin profiles

The FSW parameters of tool rotational speed, tool pin profiles and welding speed were used in these experiments based on the trial experiments [23] and study made in the previous literature work. Table 2 shows the FSW parameters and their levels, which are used to decide the design matrix for the experiments. The three factors, three levels of the L27 orthogonal array was applied to conduct the experiments based on the Taguchi method. The tensile specimens were sliced perpendicular to the welded direction using a power hacksaw and machined as per ASTM-E08 standards and which were tested in the Omega Inspection and Analytical Laboratory, Chennai).

4. Result and Discussions

The analysis of Variance (ANOVA) for the responses of tensile strength, tensile elongation and joint efficiency in dissimilar friction stir welding of titanium alloy Ti3Al2.5V alloy and AA8011 aluminium alloy are represented in Table 3 and it illustrates the most dominant contributing factors of tool rotational speed affecting the tensile strength (85.10%) and joint efficiency (85.15%), whereas for tensile elongation, the welding speed (38.72%) is the most dominant factor followed by rotational speed (20.31%) and tool pin profiles (16.04%) of the welded joints. These results conflict with tensile strength, tensile elongation and joint efficiency in friction stir welding of dissimilar non-ferrous alloys. The multiple response analysis is very important to decide the good quality of welded joints based on the proper selection parameter in friction stir welding process.

The optimization of the parameters for the tensile strength, tensile elongation and joint efficiency was done by using the Taguchi based grey relational analysis. The normalized responses, grey relational coefficients of the responses, average grey relational grade, and its rank for each experiment are shown in Table 4. The maximum average grey relational grade gives the better multiple performance in dissimilar friction stir welding process which is closer to the ideal responses.

Table 3. Analysis of Variance (ANOVA) for the responses

FSW Parameters	Degrees of Freedom	Tensile Strength (Mpa)			
		Sum of squares	Mean squares	F-Value	Contribution (%)
Rotational speed	2	1191.35	595.68	154.13	85.1
Tool pin profile	2	56.15	28.08	7.26	4.01
Welding speed	2	75.11	37.55	9.72	5.37
Error	20	77.29	3.86		5.52
Total	26	1399.91			100

Tensile Elongation (%)					
FSW Parameters	Degrees of Freedom	Sum of squares	Mean squares	F-Value	Contribution (%)
Rotational speed	2	3.916	1.958	8.14	20.31
Tool pin profile	2	3.092	1.546	6.43	16.04
Welding speed	2	7.465	3.733	15.52	38.72
Error	20	4.808	0.2404		24.93
Total	26	19.281			100
Joint Efficiency (%)					
FSW Parameters	Degrees of Freedom	Sum of squares	Mean squares	F-Value	Contribution (%)
Rotational speed	2	30.992	15.496	153.15	85.15
Tool pin profile	2	1.452	0.726	7.17	3.99
Welding speed	2	1.928	0.964	9.54	5.30
Error	20	2.024	0.101		5.56
Total	26	36.396			100

Table 4. Data preprocessing, Grey Relational coefficient and Grey relational Grade with Order

Exp. No	Tensile Strength (TS) (MPa)	Tensile Elongation (TE) (%)	Joint Efficiency (JE) (%)	Grey Relational Coefficient			Grey Relational Grade	Rank
				TS	TE	JE		
1	0.877	0.064	0.876	0.802	0.348	0.802	0.651	6
2	0.585	0.000	0.583	0.546	0.333	0.545	0.475	20
3	0.854	0.329	0.852	0.774	0.427	0.772	0.658	5
4	0.777	0.521	0.776	0.691	0.511	0.691	0.631	9
5	0.705	0.493	0.707	0.629	0.496	0.631	0.585	11
6	0.604	0.764	0.605	0.558	0.680	0.559	0.599	10
7	1.000	0.671	1.000	1.000	0.603	1.000	0.868	1
8	0.685	0.193	0.683	0.613	0.383	0.612	0.536	15
9	0.804	0.493	0.802	0.718	0.496	0.717	0.644	7
10	0.615	0.632	0.614	0.565	0.576	0.565	0.569	12
11	0.478	0.296	0.486	0.489	0.415	0.493	0.466	21
12	0.688	0.936	0.688	0.616	0.886	0.616	0.706	2
13	0.458	0.618	0.457	0.480	0.567	0.479	0.509	19
14	0.346	0.421	0.348	0.433	0.464	0.434	0.444	23
15	0.488	1.000	0.488	0.494	1.000	0.494	0.663	4
16	0.681	0.764	0.681	0.610	0.680	0.610	0.633	8
17	0.615	0.582	0.614	0.565	0.545	0.565	0.558	13
18	0.612	0.993	0.612	0.563	0.986	0.563	0.704	3
19	0.177	0.493	0.179	0.378	0.496	0.378	0.418	25
20	0.000	0.343	0.000	0.333	0.432	0.333	0.366	27
21	0.112	0.971	0.112	0.360	0.946	0.360	0.555	14
22	0.219	0.857	0.219	0.390	0.778	0.390	0.520	18
23	0.092	0.754	0.093	0.355	0.670	0.355	0.460	22
24	0.115	0.907	0.117	0.361	0.843	0.361	0.522	17
25	0.292	0.843	0.293	0.414	0.761	0.414	0.530	16
26	0.177	0.179	0.179	0.378	0.378	0.378	0.378	26
27	0.162	0.643	0.162	0.374	0.583	0.374	0.444	24

The best multiple performance was achieved for the experiment 7 which has the highest grey relational grade compared to the other experimental responses. Figure 3 shows the Pareto chart for the average grey relational grade for the welded joints. It is clearly shown that the combined effort of the rotational speed and welding speed decide the 97% of the quality of the butt welded joints and similar work has been done by Palanikumar K et al. [19]. In addition, the total mean of the Grey relational grade is also calculated and given in Table 5.

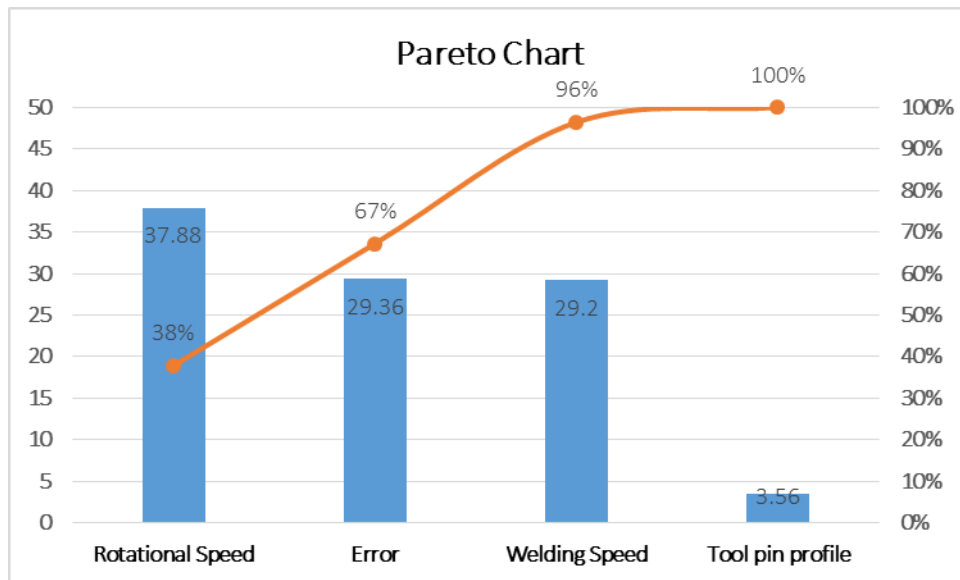


Figure 3. Pareto Chart for Grey relational Grade

The most dominant parameters based on the grey relational grade and its rank are shown in Table 5 in dissimilar friction stir welding of AA8011-H24 Aluminium alloy and Ti3Al2.5V Titanium alloy joints and Figure 4 shows the grey relational grade graph for each parameter of friction stir welding at different levels respectively. It shows that the low rotational speed, higher welding speed with the pentagon pin profile are the optimum friction stir welding parameters of the dissimilar butt joints and the average grey relational grade for all the experimental responses are shown as the dotted line in the graph and similar report as Rajyalakshmi G et al. [24].

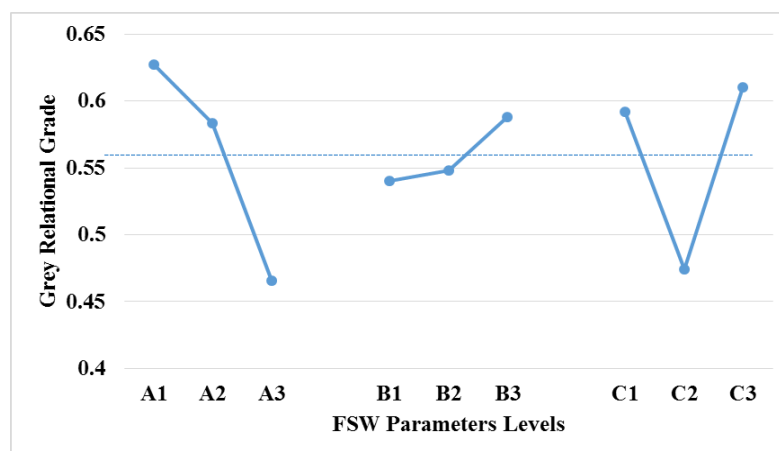


Figure 4. Response graph of grey relational grade

The confirmatory test was conducted for the optimal levels of the parameters of the welding process to improve the multiple responses of the welded joints.

$$\alpha_{\text{Predicted}} = \alpha_m + \sum_{i=1}^N (\alpha_0 - \alpha_m) \quad (4)$$

Where, α_m is the average grey relational grade for all the responses, N is the number of responses and α_0 is the average grey relational grade at the optimal level.

Table 5 Results of friction stir welding responses using the initial and optimal levels

	Initial FSW	Optimal FSW Parameters	
	Parameters	Experimental	Predicted
Optimum FSW Setting Levels	A ₁ B ₁ C ₁	A ₁ B ₃ C ₃	A ₁ B ₃ C ₃
Rotational Speed (r/min)	300	300	-
Tool Pin Profile	3	3	-
Welding Speed (mm/min)	30	40	-
Grey Relational Grade	0.651	0.710	0.7082

Improvement in grey relational grade: 0.059

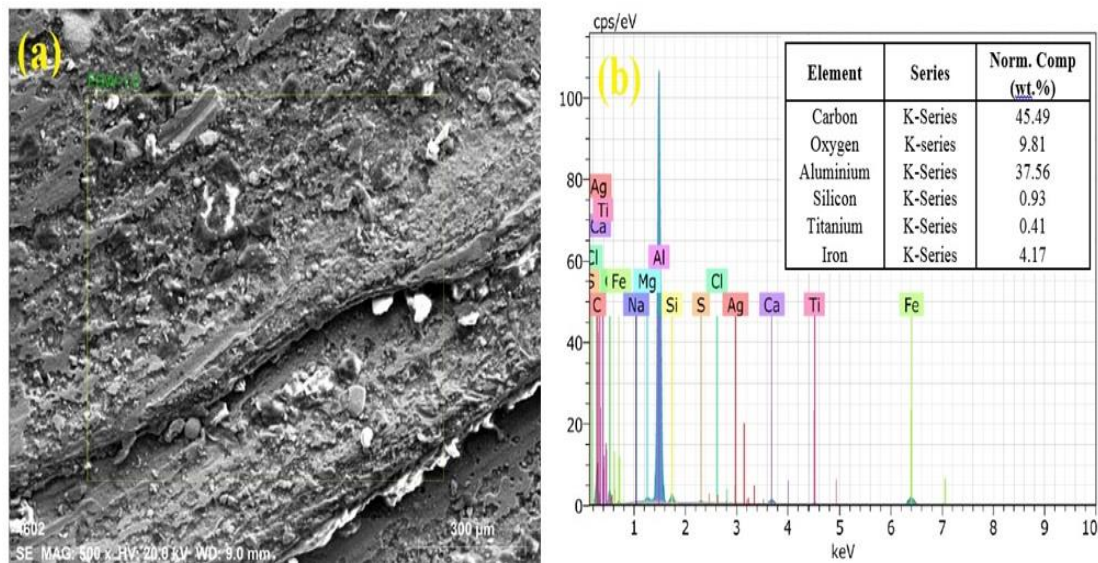


Figure 5. SEM micrograph and EDS image of the optimum process settings at the weld Interface

The comparisons of predicted and actual welding responses for multiple performance at optimal levels are shown in Table 5. There is an improvement of 0.059 of the predicted responses at optimal levels (A₁B₃C₃) compared with the initial levels (A₁B₁C₁) and the experimental response at the optimum level is much closer to the predicted responses at the optimum level was found and similar comparison done by Datta S et al. [25]. It is clearly evident from the multiple performance characteristics in the dissimilar friction stir welding process are improved through the Taguchi grey relational analysis. The microstructure of dissimilar friction stir welded joints of aluminium alloy and titanium alloy in the weld interface at the optimum process condition shown in figure 5 and showed that that the proper mixing and material flow of the material which initiates the plastic deformation between the these two nonferrous alloys using friction stir welding process.

5. Conclusions

- The Taguchi based grey relational analysis was successfully applied to optimize the multiple responses in the dissimilar friction stir welding of AA8011-H24 Aluminium alloy and Ti3Al2.5V Titanium alloy joints
- There is a significant improvement of 0.059 was found based on the grey relational grade at the optimal levels of the parameters of the dissimilar friction stir welding process
- The tool rotational speed is the dominant factor to decide the good quality of the welded joints followed welding speed and tool pin profile based on the analysis of variance on the grey relational grade.
- The microstructure of the friction stir welded joint at the weld interface for the optimum process setting showed that the material mixing was properly done due to the friction between the tool and butt surfaces of the base materials.

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