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Multiple Response Optimization with Grey Relational Analysis of Friction Stir Welding Parameters in Joining Dissimilar Aluminium Alloys by Taguchi Method

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Abstract. This paper presents a novel approach for the optimization of welding parameters on dissimilar friction stir welded joints between AA6061T-651 and AA7075T-651 aluminium alloys with multiple responses based on orthogonal array by grey relational analysis. Experiments are conducted by varying the welding parameters related to three pin profiles. In this study, welding parameters namely rotational speed, welding speed and pin profiles are optimized with the considerations of multi responses such as ultimate tensile strength and hardness. A grey relational grade is obtained from the grey analysis. Based on the grey relational grade, optimum levels of parameters have been identified and significant contribution of parameters is determined by ANOVA (Analysis of Variance). Confirmation test is conducted to validate the test result. Experimental results have shown that the responses in welding process can be improved effectively through this novel approach.

Introduction

Friction stir welding (FSW) process is a solid state joining technique considered to be the significant development over the past two decades which was invented and validated at the welding institute (TWI), United Kingdom in the year 1991[1]. In this process a non-consumable tool is to be plunged into the faying surfaces of the plates with rotation and also it moves along the joint line for weld consolidation. The joint integrity depends upon the tool geometry nature used in this process. Many studies have been conducted to characterize the resulting microstructure in welds especially in dissimilar aluminium alloys [2-7]. The grey relational analysis based on grey system theory can be used for solving the complicated interrelationships among the multi responses [8-9]. In the present study, experimental details using the Taguchi method of parameter design have been employed for optimizing multiple performance characteristics such as tensile strength and hardness for dissimilar friction stir welding with AA6061T-651 and AA7075T-651 aluminium alloys. Grey relational analysis has been considered for optimization of multiple response characteristics. Finally analysis of variance (ANOVA) and confirmation test have been conducted to validate the test result.

Material testing and specifications

Aluminium alloys of AA6061-T651 and AA7075-T651 are selected for to fabricate dissimilar joints using the FSW process; where T651 heat treatment consists of solution heat treated, stretched and artificially aged. The friction stir welding machine from CIT Coimbatore was used for welding of the plates. The thickness of the both aluminium alloy plates are 6.35 mm. Chemical compositions and the mechanical properties of AA6061-T651 and AA7075-T651 are given in Tables 1 and 2 respectively. The plates are placed in a butt configuration of 100 mm length; 50 mm width and the FSW process is carried out normal to the direction of the plates.

Table 1
Chemical composition of base aluminium alloys

Base alloys	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn
6061-T651	97.16	0.8	0.4	0.27	0.09	0.96	0.21	0.06
7075-T651	89.76	0.05	0.1	1.3	0.03	2.69	0.2	5.78

Table 2
Mechanical properties of base aluminium alloys

Aluminium alloys	Yield strength,(MPa)	Ultimate tensile strength, (MPa)	Tensile elongation, %)	Micro hardness,(VHN)
6061-T651	287.0	303.0	17.2	102.0
7075-T651	526.0	583.0	11.3	171.0

Experimental work

Dissimilar friction stir welding process is carried out by placing the high strength aluminium alloy AA7075-T651 at the retreating side (RS), and by placing the aluminium alloy AA6061-T651 at the advancing side (AS). Trail experiments are conducted to determine the working and feasible range of process parameters. After the welding, the transverse tensile specimens are prepared with reference to ASTM E8M-04 standard.

Table 3
Dissimilar friction stir welding parameters and the selected levels

S. No	Operating parameter	Symbol	Unit	Levels		
				1	2	3
1	Tool rotational speed	R	rpm	800	900	1000
2	Welding speed	W	mm/min	90	100	110
3	Tool pin profile	P	-	SS	TCT	TST

Table 4
Experimental results for L9 Orthogonal array (Actual Values)

Trial. No	Rotational speed R(rpm)	Welding speed W (mm/min)	Pin profile (P)	UTS (MPa)	Vicker's Hardness (VHN)
1	800	90	1	154.01	103.85
2	800	100	2	186.03	112.98
3	800	110	3	153.05	102.96
4	900	90	2	195.04	113.81
5	900	100	3	184.08	108.12
6	900	110	1	179.12	109.47
7	1000	90	3	172.06	104.23
8	1000	100	1	160.06	106.21
9	1000	110	2	178.1	110.35

The ultimate tensile strength and the hardness are measured from the averages of the three specimens. The assignment of the levels to the factors and the various parameters used are given in Table 3. Taguchi's L9 orthogonal array was used to design the experiments with three factors and three levels. Experiments were conducted based on the Taguchi's method which is a powerful tool used in design of experiments [17]. The experimental results for L9 orthogonal array are given in Table 4.

Multi-objective optimization using grey relational analysis

Grey relational grade is used to convert optimization problem from a multi-objective to a single-objective. The aim of this study was to determine the optimal combination of welding parameters that simultaneously Maximize Ultimate tensile strength (UTS) and Hardness (VHN). The first step of grey relational analysis is to normalize (in the range between 0 and 1) the experimental data according to the type of performance response. If the target value of the original sequence is infinite, such as UTS and VHN, it has “the-larger-the-better” characteristic. The second step is to find Grey relational coefficients which denote the relationship between the ideal and the actual experimental results.

Table 5
Normalised values,grey relational coefficients and gray relational grades of responses

Trial No	Normalised value of responses		Grey relational coefficients		GRG	Order
	UTS	VHN	UTS	VHN		
1	0.022863	0.082028	0.338493	0.352616	0.345554	8
2	0.785425	0.923502	0.699717	0.867306	0.783511	2
3	0	0	0.333333	0.333333	0.333333	9
4	1	1	1	1	1	1
5	0.738985	0.475576	0.657018	0.488079	0.572548	5
6	0.620862	0.6	0.568739	0.555556	0.562147	4
7	0.452727	0.117051	0.47743	0.361546	0.419488	6
8	0.166945	0.299539	0.375078	0.416507	0.395792	7
9	0.596571	0.681106	0.553447	0.61058	0.582013	3

Table 6
Response Table for Means

Level	R	W	P
1	0.4874	**0.5883**	0.4344
2	**0.7115**	0.5838	**0.7884**
3	0.4657	0.4924	0.4417
Delta	0.2458	0.0959	0.3540
Rank	2	3	1

Table 7
ANOVA for grey relational grade (multiple response characteristics)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% contribution
R	2	0.111096	0.111096	0.055548	8.06	0.110	28.63%
W	2	0.017577	0.017577	0.008788	1.28	0.439	4.52%
P	2	0.245617	0.245617	0.122808	17.82	0.053	63.29%
Error	2	0.013782	0.013782	0.006891	-	-	3.55%
Total	8	0.388072	-	-	-	-	-

S = 0.0830125 R-Sq = 96.45% R-Sq (adj) = 85.79%

The distinguishing coefficient is taken as 0.5 and the grey relational coefficients are calculated. The third step is to find the Grey relational grade. The higher relational grade corresponds to the closer experimental value to the ideal normalized value and the corresponding parameter combination is closer to the optimal. The fourth step is to find the grey relational ordering. The highest grey relational grade is assigned an order of 1. The grey relational order was given in Table 5. According to Table 5 the control parameter’s setting of 4 (experiment 4) had the highest grey relational grade and this meant that experiment 4 was the optimal welding factors setting for maximum tensile strength and hardness among the other experiments. Since higher multiple performance characteristics was desirable, the larger better S/N quality characteristics was adopted for grey relational grade. The optimal process parameter setting for the multiple performance characteristic was R2W1P2 (Table 6). Thus, the best combination values for maximizing the multiple performance characteristics or Grey relational grade (GRG) were rotational speed of 900 rpm, welding speed of 90 mm/min and tool pin profile as TCT (2). The response table for the means of grey relational grade is shown in Table 6. ANOVA result of the multiple performance characteristics was given in Table. 7. The analysis was made for the level of confidence 95% (the level of significance is 5%). Rotational speed, welding speed and tool pin profile influenced the multiple performance characteristics by 28.63 %, 4.52 % and 63.29 % respectively. From the analysis of this table, it could be concluded that rotational speed and tool pin profile were two dominant welding parameters that affect grey relational grade.

Confirmatory experiments

After the optimal level has been selected, it is very essential to perform a confirmation experiment for the parameter design, particularly when less number of data is utilized for optimization. The purpose of this confirmation experiment is to verify the improvement in the quality characteristics. The grey relational grade (GRG) is predicted for the optimal combination of parameters (R2W1P2) and its value is 0.97852. Lastly confirmation test was conducted using the optimum combination of parameters (R2W1P2). Table 8 shows the comparison of predicted multiple performance characteristics (GRG) with the actual one. The grey relational grade for the confirmation experiment is found to be 1. This result is within the 95% confidence interval of the predicted optimum condition. Good agreement between the predicted and actual multiple performance characteristics are being observed. The increase of the S/N ratio from the initial cutting parameters to optimal cutting parameters is 1.9305 dB.

Table 8
Results of Confirmation Experiment

	Initial welding parameters	Optimal cutting parameters	
		Prediction	Experiment
Level	R1W2P2	R2W1P2	R2W1P2
GRG	0.783511	0.97852	1.00000
SN Ratio	-2.1191	-0.1886	0

Improvement of SN ratio = 1.9305 dB

Conclusions

Friction stir welded experiments were conducted for dissimilar aluminium alloys between AA6061 T651 and AA7075 T651. The tensile strength and hardness values were collected under different welding conditions for various combinations of welding process parameters. The following conclusions were drawn.

- Grey relational analysis in the Taguchi method for the optimization of the multi response problems is a very useful tool for predicting the tensile strength and hardness in the friction stir welding of dissimilar aluminium alloys.
- From this analysis, it is revealed that rotational speed, tool pin profiles are prominent factors which affect the welding of aluminium alloys. The tool pin profile (P = 63.29 %) is the most influencing factor in determining the multiple performance characteristics or grey relational grade (GRG) followed by rotational speed (R = 28.63 %) and welding speed (W = 4.52 %).
- The best multiple performance characteristics was obtained with when friction stir welding of dissimilar aluminium alloys with the rotational speed of 900 rpm, welding speed of 90 mm/min and tool pin profile TCT(2) with the estimated multiple performance characteristics (GRG) of 0.97852. The experimental value of GRG for this combination of parameters is 1.
- The percentage of error between the predicted and experimental values of the multiple performance characteristics during the confirmation experiments is almost within 2.735 %.
- The value of multiple performance characteristics obtained from confirmation experiment is within the 95% confidence interval of the predicted optimum condition.

- The increase in the S/N ratio from the initial cutting parameters to optimal cutting parameters is 1.9305 dB.

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