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Optimizing the Process Parameters of FSW on AZ31B Mg Alloy by Taguchi-Grey Method

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Abstract: Friction Stir Welding is relatively a new solid state welding process in which no consumable materials are used. The main advantage is that it is pollution free. In the present study FSW of AZ31B are used to improve the process parameters. The experiment was carried out by Taguchi (L18) orthogonal array. Grey based Taguchi techniques were utilized to optimize the process parameters. To find out the important parameter that affects mechanical properties, an analysis of discrepancy was used. Later on, for a second order model, response surface methodology helped to develop the process parameters and performance characteristics. The hypothesis for optimal conditions was proven correct after conducting a ratification test.

Key words: Optimization · Taguchi Method · Grey Relation Analysis · Friction Stir Welding · Magnesium Alloy

INTRODUCTION

To produce a joint stronger than the fusion arc welded joint, the Friction Stir Welding process (FSW) can be used. Many applications such as aerospace, automotive and ship building industries, [1] widely use the friction stir welding to weld the light weight materials, such as aluminum, magnesium and titanium. More effective welding and joining techniques are essential, however for further usage of magnesium alloys. Commonly encountered defects in fusion welded joints [2] such as oxide inclusions, porosity, cracks and distortions can be reduced using the joining technique of (FSW), because it has a great potential for magnesium alloys. To develop quality joints, the process variables like the rotational speed, travel speed and tool geometry are vital [3].

To ensure a successful and efficient welding cycle [4], the tool speed and tool geometry must be chosen with care, as both of these parameters are considerably important. The relationship between the welding speeds and the heat input during welding is complicated, but usually it is stated that increasing the rotation speed or decreasing the traverse speed will result in a hotter weld. To allow the extensive plastic flow required and to minimize the forces acting upon the tool, the material

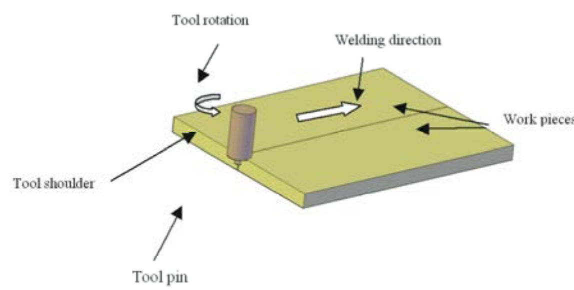

Fig. 1: Tool and work pieces

surrounding the tool must be hot, so that a successful weld can be produced. The tool might break under extreme conditions, or voids or other flaws might be present in the stir zone if the material is too cold [5]. The tool and work piece arrangement in FSW is shown in Figure 1 [6].

In a study R. Nadan *et al*. [7] studied about heat generation; heat transfer and plastic flow during friction stir welding and the properties of welded materials and formation of defects. He optimized the process parameters in FSW of an Aluminum Alloy AA 5083 which gave multiple responses based on the orthogonal array with grey relational analysis. Thus, the L9 orthogonal array of the Taguchi experimental style is used for optimizing the friction stir welding process parameters for the tensile strength of the FSW welds [8].

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The process parameters, rotational speed of the tool in rpm, traverse speed in mm/min and the axial force in KN are considered for optimization.

Focused on the multi-response optimization of the FSW process for an optimal parametric combination using the Taguchi based Grey relational analysis. Here the parameters are rotating speed, welding speed and tool shoulder diameter which were optimized during the experiments using Taguchi L8 orthogonal array [9]. Experiments were conducted using (10,11) Taguchi Statistical techniques to identify the relevant factors by conducting relatively a few number of experiments. They adopted the Taguchi L9 method to analyze the effect of rotational speed, traverse speed and axial force on tensile strength of RDE-40 aluminum alloy for the FSW process. Shivani Dafardar [12] used Analysis of Variance (ANOVA), to identify the process parameters which are statistically relevant.

In the present work, an attempt has been made to carry out the experiments based on the L18 orthogonal array. In order to obtain a quality weld, the process parameters are optimized using Taguchi based grey relation analysis.

Optimization Using Taguchi Based Grey Relation Method: To design a high-quality system, a powerful tool also known as the Taguchi method, can be used. Not only does this method provide an efficient approach, but it provides a systematic approach to optimize designs for better performance and quality [13]. A design that has minimized the number of experiments is the orthogonal array experimental design. To determine the improved performance of the process parameter which increases the quality of the characteristics, the S/N ratio can be used. The characteristics of the S/N ratio performance can be divided into many factors: the smaller the better, if nominal the best, the factor larger the better was picked, which optimized the tensile strength and hardness. For higher-the-better performance characteristic of the loss function can be expressed as

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{ij}^{2}} \tag{1}$$

The lower-the better factor was preferred to minimize the ductility. For the lower-the-better performance factor, the loss function can be expressed as:

$$\eta_{ij}=(1/n\Sigma yij^{2}) \tag{2}$$

Lij is the loss function of the ith performance factor of the jth experiment and yijk is the experiment at the kth trial and n is the number of trials.

The loss function can be further transformed into an S/N ratio. To determine the deviation of the performance characteristic from any desired value, the S/N ratio was used in the Taguchi Method [14]. The S/N ratio ηij for the ith performance factor in the jth experiment can be expressed as

$$\eta_{ij} = -10 \log (L_{ij}) \tag{3}$$

The Taguchi method is applicable to increase the single response characteristic problems. Hence, to amplify the multi-response characteristic problem, the grey relation observation is selected in this investigation [15]. To analyze the relatable grade for discrete sequences, the grey relation technique was used. Firstly, the S/N ratio is normalized into a range between zero and unity [16]. The normalized S/N ratio xij for the ith performance characteristic in the jth experiment can be expressed as

$$\chi_{ij} = \frac{\eta_{ij} - \min\eta_{ij}}{\max\eta_{ij} - \min\eta_{ij}} \tag{4}$$

After the grey relational generation χ_{ij} is the value, min η_{ij} is the smallest value η_{ij} of the jth response. Then using the normalized value the grey relation coefficient is determines. The grey relational coefficient $æ_{ij}$ for the ith performance characteristic in the j[th] experiment can be expressed as

$$\zeta_{ij} = \frac{\min_i \min_j \left|\chi_i^0 - \chi_{ij}\right| + \zeta \max_i \max_j \left|\chi_i^0 - \chi_{ij}\right|}{\left|\chi_i^0 - \chi_{ij}\right| + \zeta \max_i \max_j \left|\chi_i^0 - \chi_{ij}\right|} \tag{5}$$

Where $\chi 0_i$ is the ideal normalized S/N ratio for the ith performance characteristic and æ is the distinguishing coefficient which is defined in the range of $0 \le \xi \le 1$. Next averaging the grey relation coefficient gives the grey relation grade. The grey relation grade γ_j can be gained,

$$\gamma_j = \frac{1}{m}\sum_{k=1}^{n} w_i \zeta_{ij} \tag{6}$$

Where γ_j is the grey relational grade for the j[th] experiment w_i the weighting factor for the i[th] performance characteristics. These results show that complex multiple performance characteristics can be converted into a single response grey relation grade.

Table 1 : Base material chemical composition (weight in %)

Alloy	Mg	Al	Mn	Zn	Si	Cu	Ni	Fe	Ca
Base material	97	2.5-3.5	0.20	0.60-1.40	0.10 max	0.050 max	0.005max	0.005 max	0.040

Table 2: Welding Parameters and their Levels

Process Parameter/Level	Symbols	Low (1)	Medium (2)	High (3)
Pin Length (PL) in mm	PL	3.5	-	4.5
Rotating Speed (RS) in rpm	RS	1000	1200	1400
Welding Speed (WS) in inch/min	WS	1.2	1.6	2

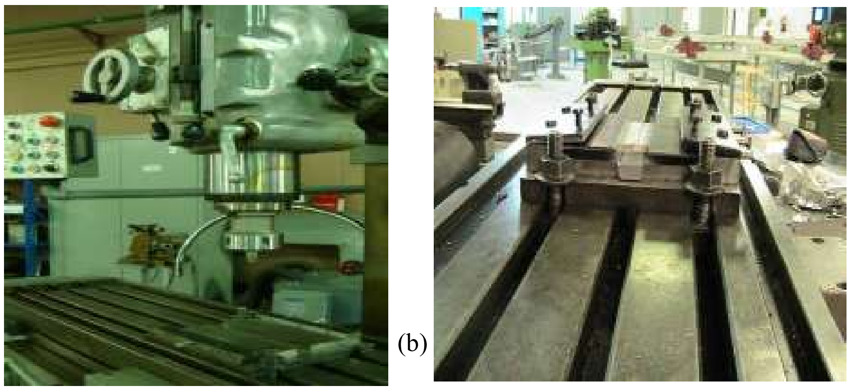

Fig. 2: (a) Vertical Milling Machine with fixture and (b) Fixture

Fig. 3: Welded joints

Experimental Setup : A sheet of Magnesium AZ31B alloy with 120 mm length, 60 mm width and 6 mm thickness was used in this study. The base material's chemical composition is given in Table 1. FSW of the parts were carried out on a study of Vertical Milling machine as shown in figure 2 (a) and figure 2(b) shows the fixture arrangements. Special clamping methods were used to have a firm gripping of the work pieces.

The Zwick Ultimate Tensile Testing machine and hardness testing machine were used to test the tensile strength, elongation and hardness. The Table 2 below shows the identified process parameters and their levels. The L18 orthogonal array is selected as per standard suggested by Taguchi approach [17] and is shown in Table 3.

Table 3: L18 orthogonal array

Ex. No	PL	RS	WS
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	3	1	1
11	3	1	2
12	3	1	3
13	3	2	1
14	3	2	2
15	3	2	3
16	3	3	1
17	3	3	2
18	3	3	3

Eighteen pieces were welded as per the experimental plan. Fig. 3 shows the welded specimens obtained according to the L18 experiment condition.

RESULTS AND DISCUSSION

S/N Ratio: The experimental results for tensile strength, ductility and hardness and the calculated S/N ratio have given in Table 4. For different performance characteristics, it's notable that the parameter levels may be varied. Hence these parameters cannot be optimized by Taguchi S/N ratio. For optimization multi response characterization is necessary. In this experiment, to optimize the multi objective problem the complex S/N values are used in the grey relation analysis.

Grey Relation Analysis: The normalized S/N ratio and grey relation coefficient for ultimate tensile strength, ductility and hardness is shown in Table 5. Usually, a larger normalized value exhibits the better performance and the best normalized value is equal to one [18]. The relationship between the ideal and the measured value is shown by the grey relation coefficient [19]. The total mean grey relation grade and mean for each level of the process parameters is shown in Table 6. Through observation, it has been concluded that experiment 15 shows the best multiple performance characteristics when compared with other 18 investigations. Figure 4 shows the optimal level of the three process parameters.

Table 4: Experimental Result and S/N Ratio

PL	RS	WS	Hardness	Ductility	UTS	S/N for Hardness	S/N for Ductility	S/N for UTS
3.5	1000	1.2	57.1	7.86	185	35.133	-17.908	45.343
3.5	1000	1.6	55.74	7.67	194	34.923	-17.696	45.756
3.5	1000	2	58.62	7.38	190	35.361	-17.361	45.575
3.5	1200	1.2	60.63	7.14	196	35.654	-17.074	45.845
3.5	1200	1.6	70.54	7.28	206	36.969	-17.243	46.277
3.5	1200	2	64.09	6.85	214	36.136	-16.714	46.608
3.5	1400	1.2	67.32	7.14	211	36.563	-17.074	46.486
3.5	1400	1.6	59.52	6.91	231	35.493	-16.790	47.272
3.5	1400	2	66.7	7.04	217	36.483	-16.951	46.729
4.5	1000	1.2	58.32	7.15	201	35.316	-17.086	46.064
4.5	1000	1.6	67.34	7.04	218	36.565	-16.951	46.769
4.5	1000	2	69.24	6.98	213	36.807	-16.877	46.568
4.5	1200	1.2	70.41	6.82	234	36.953	-16.676	47.384
4.5	1200	1.6	70.68	6.61	240	36.986	-16.404	47.604
4.5	1200	2	67.95	6.54	248	36.644	-16.312	47.889
4.5	1400	1.2	70.2	7.1	227	36.927	-17.025	47.121
4.5	1400	1.6	73.21	6.84	233	37.291	-16.701	47.347
4.5	1400	2	74.42	6.91	222	37.434	-16.790	46.927

Table 5: Normalized, Coefficient and grade of UTS, Ductility and Hardness

UTS	Normalize	Coefficient	Ductility	Normalize	Coefficient	Hardness	Normalize	Coefficient	Grey Grade
45.343	0.000	0.500	-17.908	0.000	0.500	35.132	0.083	0.522	0.507
45.756	0.162	0.544	-17.696	0.133	0.536	34.923	0.000	0.500	0.527
45.575	0.091	0.524	-17.361	0.343	0.603	35.360	0.174	0.548	0.558
45.845	0.197	0.555	-17.074	0.523	0.677	35.653	0.291	0.585	0.606
46.277	0.367	0.612	-17.243	0.417	0.632	36.969	0.815	0.844	0.696
46.608	0.497	0.665	-16.714	0.749	0.799	36.134	0.482	0.659	0.708
46.486	0.449	0.645	-17.074	0.523	0.677	36.562	0.653	0.742	0.688
47.272	0.758	0.805	-16.790	0.701	0.770	35.493	0.227	0.564	0.713
46.729	0.544	0.687	-16.951	0.600	0.714	36.482	0.621	0.725	0.709
46.064	0.283	0.582	-17.086	0.515	0.674	35.316	0.157	0.542	0.600
46.769	0.560	0.694	-16.951	0.600	0.714	36.565	0.654	0.743	0.717
46.568	0.481	0.658	-16.877	0.646	0.739	36.807	0.751	0.800	0.733
47.384	0.802	0.834	-16.676	0.772	0.815	36.952	0.808	0.839	0.829
47.604	0.888	0.899	-16.404	0.943	0.946	36.985	0.822	0.849	0.898
47.889	1.000	1.000	-16.313	1.000	1.000	36.644	0.686	0.761	0.920
47.121	0.698	0.768	-17.025	0.554	0.691	36.926	0.798	0.832	0.764
47.347	0.787	0.824	-16.701	0.757	0.804	37.291	0.943	0.946	0.858
46.927	0.622	0.726	-16.790	0.701	0.770	37.433	1.000	1.000	0.832

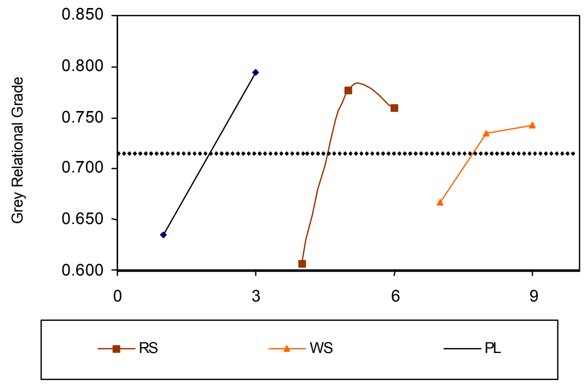

Fig. 4: Grey relations Grade

Table 6: Response table for Mean of grey grade

Parameters	1-Mean	2-Mean	3-Mean
PL	0.6348		0.7948
RS	0.6070	0.7767	0.7607
WS	0.6657	0.7352	0.7435
Total	1.9074	1.5118	2.2989
Mean grey	0.7148		

Table 7: ANOVA for Grey Grade

Parameters	DOF	Sum of Square	Mean Square	F	Contribution Percentage
PL	6	0.1152	0.0192	1.4741	45.096
RS	6	0.1053	0.0176	1.3475	41.225
WS	5	0.0219	0.0044	0.3365	8.579
Error	0	0.0130			5.098
	17			TOTAL	100.00

Table 8: Results of ratification test

	PL	RS rpm	WS Inch/mm^2	UTS N/mm2	% Elongation	Brinell Hardness
Initial Parameter	4.5	1200	2	248	6.54	67.95
Predicted Parameter	4.5	1200	2	252	6.72	65.35

ANOVA: In this study, to investigate the significance of the process parameters on performance characteristics ANOVA was used. The results of ANOVA for Grey relation grade values are shown in Table 7. In this situation, the parameter, pin length plays a major role on the performance characteristics and the predecessor is rotational speed. Optimal welding process parameters are pin length of 4.5 mm (level 3), rotational speed of 1200 rpm (level 2) and welding speed of 2 inch/mm and are shown in the analysis.

Response Surface Regression: The second order mathematical model has developed for the tensile strength, ductility and harness can be expressed as the function of pin length, rotating speed and welding speed. Expressed below are the relationships between performance characteristics and welding process parameters.

- $UTS = -648.094 + 193.679\,WS + 0.534RS + 61.483PL - 44.792WS^2 - 1.054\times10^{-4}RS^2 - 0.014\,WS\,(RS) - 3.333WS\,(PL) - 0.018RS\,(PL)$
- $Ductility = 29.102 - 1.738WS - 0.016RS - 2.064PL + 0.109WS^2 + 3.032\ 10^{-6}\,RS^2 + 0.03WS\,(RS) + 0.096WS\,(PL) + 0.0008RS\,(PL)$
- $Hardness = -91.282 + 23.814WS + 0.114RS + 1.573PL - 4.719WS^2 - 2.226\ 10^{-5}\,RS^2 - 0.099\,WS\,(RS) + 3.467WS\,(PL) - 1.489\times10^{-4}\,RS\,(PL)$

Ratification Test and Result: Finally the experiments were conducted to verify the improvement in tensile strength based on the predicted optimized input signal (variables) and tested their strength and hardness. It can be observed that there was a considerable improvement in tensile strength as shown in table 8, but hardness had no significant change.

CONCLUSION

To optimize the welding process parameters of welding the sheet of AZ31B magnesium alloy the grey based Taguchi method was applied in this investigation. The results are summarized as follows:

- Observation concludes that the process parameters of welding speed of 2 inch/min, with the rotational speed of 1200 rpm and with a pin length of 4.5 gives better results when welding.
- The calculation of grey relational grade helped to quantify the integrated performance in pin length, welding speed and rotational speed on weld quality.
- The ANOVA results emphasis that parameter pin length contribution was 45.09% and has more influence on quality performance of weld.
- The second order responses surface model for performance characteristics have been developed for the observed data. The predicted and measured values fall closely and shows that developed models are reliable for prediction.

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