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Evaluating Optimal Process Parameters in Dissimilar Friction Stir Welding of Al Alloys

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Abstract: ***This study is made to determine the near optimal process parameters (speed, feed, axial force) of Friction Stir Welding (FSW) of dissimilar aluminum alloys AA 6262 and AA7075 using gray relational analysis by simultaneously considering multiple output parameters tensile strength (UTS) and hardness (VHN). Experiments were performed with three process parameters such as tool rotational speed, weld speed and axial force considering three levels of each. All the possible combinations are used for the experimentation. Optimum process parameter combination of the FSW of dissimilar aluminum alloys was obtained via gray relational grade obtained from the gray relational analysis. Confirmation experiment has been conducted to validate the optimized parameters. The predicted and initial parameters have the better aspect ratio. The optimal process parameters were identified in order to find the quality of the welded specimens.***

Keywords - FSW, Gray Relational Analysis, Dissimilar Aluminium alloys.

I. INTRODUCTION

In contrast to many of the fusion welding processes that are routinely used for joining structural alloys, FSW is an emerging solid state joining process in which the material that is being welded does not melt and recast. FSW was invented at The Welding Institute (TWI), UK in 1991 [1-4]. FSW is a continuous, hot shear, autogenous process involving a non-consumable rotating tool of harder material than the substrate material [5,6]. Defect-free welds with good mechanical properties have been made in a variety of aluminium alloys, even those previously thought to be not weldable. When alloys are friction stir welded, phase transformations that occur during the cooling of the weld are of a solid-state type. Due to the absence of parent metal melting, the new FSW process is observed to offer several advantages over fusion welding. In order to obtain improved weld properties, it is necessary to select the most appropriate process parameters. The material flow behavior is predominantly influenced by the parameters namely FSW tool profiles, FSW tool dimensions and FSW process parameters namely weld speed, tool rotational speed and axial force [7-10].

Recently, the application of aluminum and its alloys in automotive and aerospace industries is widely growing. In machining of aluminum and its alloys,

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Since they have comparatively low weight density ratio and highly adhesive characteristics, more effective lubrication is often necessary, though they are not so hard **[11].**

In the present study, the dissimilar Aluminum alloys AA 6262-T6 and AA 7075-T6 of 6mm thick plates were joined by FSW considering the welding parameters as tool rotational speed, weld speed and axial force with a cylindrical threaded tool made of H13 tool steel.

A sufficient number of experiments were conducted for finding the working limits of the process parameters, in order to obtain defect less welded specimens. After determining the working limits, experiments were conducted for all the possible combinations of the considered process parameters. Most of the published works have focused on optimization of process parameters for machining of metals [12-17], where as in the present work the same optimization is applied to the FSW of dissimilar aluminium alloys to find the most sensitive process parameter with the help of gray relational analysis (GRA) by optimizing the FSW process parameters for better performance characteristics. GRA was initiated by Professor Ju-Long Deng, the famous scientist and founder of gray system theory, Huazhong University of Science and Technology [18].

II. EXPERIMENTATION

Plates of 6mm thick of 6262-T6 and 7075-T6 Al alloys were friction stir butt welded using H13 tool steel tool of cylindrical threaded pin [19] profile with 18mm shoulder diameter, 6mm pin diameter with 1.25mm pitch of the tread. The AA 6262 alloy was on the advancing side of the tool while the AA 7075 alloy was on the retreating side Chemical compositions in weight percentage and mechanical properties at room temperature of base metal (BM) s AA6262 and AA7075 are presented in the Table 1 and Table 2 respectively. Square butt joint configuration was prepared to fabricate the FSW joints. The initial joint configuration was obtained by securing the plates in position using a special fixture and mechanical clamps. The direction of welding was normal to the rolling direction. An indigenously designed and developed machine (15 HP; 3000 RPM; 25 kN) was used to fabricate the joints. The welding parameters and tool dimensions are presented in Table 3. Hardness testing was carried out using Vickers pyramid hardness testing machine (Make: Leco and LV 700) with a load of 5 kg. Hardness survey along the transverse direction of the weld was conducted with hardness measurements at regular intervals of 2 mm from the centerline of the weld on both sides of the weld.

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The welded joints were sliced using power hacksaw and then machined to the required dimensions on EDM to prepare tensile specimens. American Society for Testing of Materials guidelines (ASTM E8) was followed for preparing the test specimens. Tensile test was carried out on 10 Tonne, computer controlled Universal Testing Machine. All the specimens are mechanically polished before tests to eliminate the surface irregularities [20,21]. The specimen finally fails after necking. The ultimate tensile strength was evaluated.

Table 1: Chemical Composition of AA6262-T6 and AA7075-T6

Material	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Al
AA6262	0.65	0.313	0.215	0.076	0.90	0.091	0.065	0.081	97.597
AA7075	0.104	0.254	1.56	0.063	2.32	5.95	0.191	0.055	84.496

Table 2: Mechanical properties of BMs

Material	UTS (MPa)	Hardness (VHN)
AA6262-T6	346	108
AA 7075-T6	589	195

Table 3: Process Parameters and Tool Dimensions

Sl. No	Process parameters	Values
1	Toolrotationalspeed, rpm	1000,1200,1400
2	Weld speed (mm/sec)	0.4,0.6,0.8
3	Axial force (kN)	8,9,10
4	D/d ratio of tool	3.0
5	Pin length(mm)	5.8
6	Toolshoulderdiameter,mm	18
7	Pin diameter (mm)	6
8	Pitch of the thread (mm)	1.25

III. GRAY RELATIONAL ANALYSIS AND DATA PREPROCESSING

In a complex multivariate system, the relationship among the various factors is usually unclear. Such

Systems are often called as "gray" implying poor, incomplete, and uncertain information. GRA is an impacting measurement method in gray system theory that analyzes uncertain relations between one main factor and all the other factors in a given system. When experiments are ambiguous or when the experimental method cannot be carried out exactly, GRA helps to compensate for the shortcomings in statistical regression [22-24]. Data pre processing in GRA is normally required since the range and unit in one data sequence may differ from the others. In addition, it is a process of transferring the original sequence to a comparable sequence. For data preprocessing, "the higher tensile strength and the higher hardness" are considered as the indicative responses of better welds in FSW process. Then, it has a characteristic of the "higher is better" if the target value of original sequence is infinite. The original sequence can be normalized as following [23-25]

$$x_i^*(k) = \frac{x_i^o(k) - min x_i^o(k)}{max x_i^o(k) - min x_i^o(k)} \qquad (1)$$

where i=1,…, m; k=1,…,n. m is the number of experimental data items and n is the number of parameters. $x_i^o(k)$denotes the original sequence, $x_i^*(k)$ denotes the sequence after the data preprocessing, max $x_i^o(k)$ is the largest value of $x_i^o(k)$ whereas min $x_i^o(k)$ denotes the

smallest value of $x_i^o(k)$, and xo is the desired value .when the "lower is better" is a characteristic of the original sequence, the original sequence should be normalized as following [23-25] :

$$x_i^*(k) = \frac{max x_i^0(k) - x_i^o(k)}{max x_i^o(k) - min x_i^o(k)} \qquad (2)$$

In GRA, the measure of the relevancy between two systems or two sequences is defined as the gray relational grade. When only one sequence, $x^0(k)$, is available as the reference sequence and all other sequences serve as comparison sequences, it is called a local gray relation measurement. After data preprocessing is carried out, the gray relation coefficient **ξi (k)** for the k[th] performance characteristics in the i[th] experiment can be expressed as following [23-25

$$\xi_i(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{oi}(k) + \zeta\Delta_{max}} \qquad (3)$$

Where, Δ_0i is the deviation sequence of the reference sequence and the comparability sequence.

$$\Delta_{oi} = \|x_o^*(k) - x_i^*(k)\| \qquad (4)$$

$$\Delta_{min} = \min_{\forall j \in i} \min_{\forall k} \|x_o^*(k) - x_j^*(k)\| \qquad (5)$$

$$\Delta_{max} = \max_{\forall j \in i} \max_{\forall k} \|x_o^*(k) - x_j^*(k)\| \qquad (6)$$

$x_0^*(k)$ denotes the reference sequence and $x_i^*(k)$ denotes the comparability sequence. ζ is distinguishing or identification coefficient: ζ ∈ [0, 1] (the value may be adjusted based on the actual system requirements). A value of ζ is the smaller and the distinguished ability is the larger. ζ=0.5 is generally used. After the gray relational coefficient is derived, it is usual to take the average value of the gray relational coefficients as the gray relational grade [23-25]. The gray relational grade is defined as following:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \qquad (7)$$

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Table 4: Experimental results

Exp. No	Axial force(kN)	Weld speed (mm/sec)	Tool rotational speed (rpm)	UTS (MPa)	Hardness (VHN)
1	8	0.4	1000	224.71	100.24
2	8	0.4	1200	236.13	110.15
3	8	0.4	1400	233.9	106.37
4	8	0.6	1000	231.21	104.78
5	8	0.6	1200	242.63	112.42
6	8	0.6	1400	236.37	109.09
7	8	0.8	1000	219.87	98.36
8	8	0.8	1200	231.6	107.05
9	8	0.8	1400	226.36	103.43
10	9	0.4	1000	229.67	105.79
11	9	0.4	1200	241.74	115.94
12	9	0.4	1400	237.59	111.16
13	9	0.6	1000	238.86	112.8
14	9	0.6	1200	249.24	128.9
15	9	0.6	1400	247.76	122.5
16	9	0.8	1000	225.79	103.65
17	9	0.8	1200	239.89	112.63
18	9	0.8	1400	234.86	108.17
19	10	0.4	1000	227.52	103.41
20	10	0.4	1200	239.03	113.48
21	10	0.4	1400	230.71	109.93
22	10	0.6	1000	232.01	107.25
23	10	0.6	1200	243.56	116.03
24	10	0.6	1400	236.59	112.15
25	10	0.8	1000	221.94	101.15
26	10	0.8	1200	235.18	110.74
27	10	0.8	1400	228.17	106.73

Table 5: The sequences after data preprocessing for performance characteristics

Exp. No	Tensile Strength(MPa)		Hardness(VHN)	
	Comparability[a] sequence	Deviation sequence	comparability sequence	Deviation sequence
1	0.1647	0.8356	0.061	0.929
2	0.553	0.447	0.386	0.614
3	0.477	0.553	0.262	0.737
4	0.386	0.614	0.210	0.790
5	0.774	0.226	0.460	0.540
6	0.567	0.439	0.351	0.649
7	0.000	1.000	0.000	1.000
8	0.339	0.601	0.284	0.716
9	0.220	0.779	0.166	0.834
10	0.333	0.667	0.243	0.757
11	0.744	0.256	0.575	0.425
12	0.603	0.397	0.419	0.581
13	0.646	0.354	0.472	0.528
14	1.000	0.000	1.000	0.000
15	0.949	0.051	0.790	0.210
16	0.201	0.799	0.173	0.827
17	0.681	0.319	0.467	0.533
18	0.510	0.490	0.334	0.666
19	0.262	0.740	0.165	0.835
20	0.652	0.348	0.495	0.505
21	0.369	0.631	0.378	0.622
22	0.410	0.586	0.291	0.709
23	0.896	0.193	0.578	0.422
24	0.569	0.431	0.451	0.549
25	0.072	0.930	0.091	0.909
26	0.521	0.479	0.405	0.595
27	0.282	0.718	0. 274	0.726

[a] Reference sequence for tensile strength and hardness=1.0000

Table 6: The evaluated gray relational coefficients & gray relational grades for 27 comparability sequences

Exp. No	Gray relational coefficient		Gray relational grade	Rank
	Tensile strength,UTS (MPa)	Hardness (VHN)		
1	0.374	0.347	0.240	25
2	0.527	0.448	0.325	11
3	0.474	0.403	0.292	17
4	0.448	0.387	0.278	19
5	0.688	0.480	0.389	5
6	0.532	0.435	0.323	12
7	0.333	0.333	0.222	27
8	0.454	0.411	0.288	18
9	0.390	0.374	0.254	23
10	0.428	0.397	0.275	20
11	0.661	0.540	0.400	4
12	0.557	0.462	0.339	9
13	0.585	0.486	0.357	8
14	1.000	1.000	0.666	1
15	0.907	0.704	0.537	2
16	0.384	0.376	0.253	24
17	0.610	0.484	0.364	6
18	0.505	0.428	0.311	14
19	0.403	0.374	0.259	22
20	0.589	0.497	0.362	7
21	0.442	0.445	0.295	16
22	0.460	0.413	0.296	15
23	0.721	0.542	0.421	3
24	0.537	0.476	0.337	10
25	0.349	0.354	0.234	26
26	0.510	0.456	0.322	13
27	0.410	0.407	0.272	21

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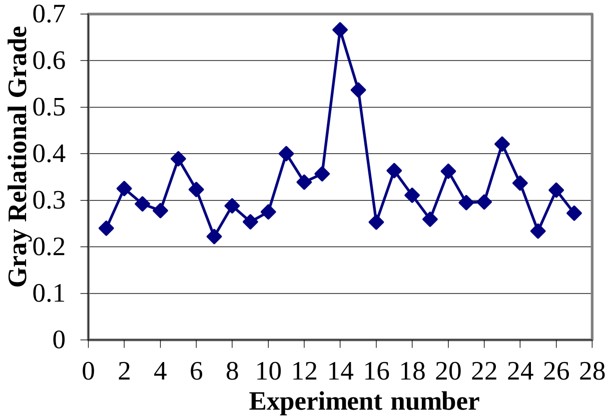

Fig 1. Gray relational grades for multi performance

IV. RESULTS AND DISCUSSION

In machining operations, maximum tensile strength and maximum hardness are an indication of better performance. For data preprocessing in the GRA process, tensile strength and hardness were taken as the "higher is better" and "higher is better", respectively. Let the results of 27 experiments be the comparability sequences $x_i^o(k)$, i=1-27, k=1. The results for the 27 experiments were presented in the Table 4. All the sequences after data preprocessing using eq.1 and eq.2 are listed in Table 5 and denoted as $x_0^*(k)$ and $x_i^*(k)$ for reference sequence and comparability sequence, respectively. The distinguishing coefficient ζ can be substituted into Eq. 3 to produce the gray relational coefficient. The gray relational coefficients and grade values for each of the 27 experiments were calculated by applying the Eqs.3–7 and were presented in Table 6. According to the performed experimental design, it is clearly observed from Table 6 and Fig 1, that the process parameters setting of the experiment number14 has the highest gray relational grade. Therefore, the machining parameters in experiment 14 are the optimal machining parameters for maximum tensile strength and maximum hardness simultaneously (i.e., the best multi performance characteristics) among the 27 experiments. In addition to the determination of optimum process parameters for better tensile strength and hardness, the response table calculates the average gray relational grade for each level of the process parameters. The procedure includes the gray relational grades with factor level for each column in the design Table 4 and the average of them. The gray relational grade values for each level of the process parameters were calculated using the same method and were presented in Table 7. The greater value of the gray relational grade indicates the comparability sequence has a stronger correlation to the reference sequence [24]. In other words, regardless of category of the performance characteristics, a greater gray relational grade value corresponds to the better performance [26]. Therefore, the optimal level of the process parameters is the level with the greatest gray relational grade value. The optimal machining performance for both the maximum tensile strength and the maximum hardness was obtained for 1200 rpm tool rotational speed, 0.6 mm/sec weld speed, and 9kN axial force combination. Table **7** depicts the effect of FSW process parameters on the multi performance characteristics (the tensile strength and the hardness). The greater value in Table 7 gives the better tensile strength and hardness. As listed in Table 7, the differences between the maximum and the minimum value of the gray relational grade of the process parameters were as follows: 0.0990 for axial force, 0.120 for weld speed, and 0.125 for tool rotational speed. The most effective factor on performance characteristics was determined by comparing these values. This comparison presents the level of significance of the controllable factors over the multi performance characteristics. The most effective controllable factor was the maximum of these values. Here, the maximum value among all the maximum–minimum values is 0.125. The value demonstrated that the tool rotational speed has the strongest effect on the multi performance characteristics among the other process parameters. On the other hand, the role that every controllable factor plays over the multi performance characteristics can be obtained by examining these values. The order of importance of the controllable factors on the multi performance characteristics in the FSW operation can be listed as factors tool rotational speed, weld speed, and axial force as 0.125> 0.120>0.099. Thus the factor 'tool rotational speed' was the most effective factor on the multi performance characteristics and the factor 'axial force' was less effective indicating that the FSW performance was strongly affected by the tool rotational speed.

Table7: Individual Gray relational grade for process parameters

Process Parameters	Level 1	Level 2	Level 3	(Maximum-Minimum)
Axial Force	0.290	0.389*	0.310	0.099
Weld speed	0.309	0.400*	0.280	0.120
Tool rotational speed	0.268	0.393*	0.296	0.125*

V. CONCLUSIONS

The GRA based on the response table was conducted as a way of studying the optimization of FSW process factor level. The maximum tensile strength and the hardness were selected to be the quality targets. From the response table of the average gray relational grade, the largest value of gray relational grade for the FSW parameters was found. The tool rotational speed was the strongest factor among the other FSW process parameters. The importance of the controllable factors on the multi performance characteristics was in the order of tool rotational speed > weld speed > axial force. This study indicated clearly, that the GRA accomplished effectively the optimization of tensile strength and hardness in FSW operation at multiple quality requests.

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