Volume 25 Issue 04, 2022 ISSN: 1005-3026 https://dbdxxb.cn/ Original Research Paper

MULTI OBJECTIVE OPTIMIZATION OF DISSIMILAR ALUMINUM ALLOY FRICTION STIR WELDING PROCESS CONTROL VARIABLES

S.D.Kumar[1] R.Pugazhenthi[2]

[1]Assistant Professor, SRM Institute of Science and Technology, Ramapuram Campus, Chennai-89

[2]Professor, Vels Institute of Science and Technology and Advanced Studies, Chennai-117

E.mail: sdkumar1973@gmail.com, pugal4@gmail.com

Abstract

The progress of friction stir welding has offered a different approach for fabricating superior class weld. In this paper deals with multi objective optimization of process control variables influencing weld features in customized friction stir butt welding of 6 mm thick dissimilar plates of AA7075 and AA6101 using Taguchi grey relational approach. The L27 orthogonal array has been employed to design the experimental trails and the joints have been fabricated in a laboratory stage friction stir welding machine by varying tool revolving speed, worktable translational speed, tool plunge force and tool pin shape. After welding, the weld tensile properties and impact strength have been evaluated using universal testing machine. Based on the experimental results optimum levels of process control variables have been noted using grey relation rating and compared with confirmation test.

Keywords : Friction stir welding, mechanical properties, multi objective, dissimilar aluminum alloy, Grey Relation Grade.

1 Introduction

In technology growth, the scientists and technologies are handling extremely challenging problems in the area of metal joining technology. The problem of following the conventional joining methods can mainly be attributed to novel materials with low welding strength. Scientists in the field of material science are novel frontier materials having a high strength, hardness, toughness and other diverse behaviors. The welding of metals in these materials is much more difficult by conventional methods. In the two decades, an innovative solid-state joining method generally called as Friction stir welding (FSW) was invented and patented by The Welding Institute (TWI) in United Kingdom in the year 1991[1]. The need for FSW was addressed in the first paragraph as FSW was environmentally friendly and accessible to materials with a high strength to weight ratio and does not have welding defects such as hot cracks and porosity [2, 3]. Genetic programming (GP) is a comparatively new approach to advanced computation, with the key benefit of this method being the estimation of efficient predictive math's models or equations without any assumption as to the potential type of functional relationship [4]. Owing to low precipitate dispersal, and/or rather than grain size in the weld, the hardness decreased with increased tool traverse speed. The R^2 values for the projected model of all the properties were obtained nearly 90%, its revealed a good agreement between the independent variables and the response data [5]. Many combinations of process

Submitted: 16/11/2022 **Accepted**: 05/12/2022

control variables were formed using L18 orthogonal array. By using Principal Component Analysis (PCA) it was noticed that weightage of 45.36 %, 44.51% and 10.11% hardness tensile strength and power consumptions respectively. Optimal process parameters were obtained using Multi-Objective Ratio Analysis (MOORA) optimization, which results in the maximization of tensile strength and hardness with lower power consumption [6]. The difference between the higher and lower value of the gray relation grade of the variables of the FSW operation is as follows: 0.2756 for tool rotational speed, 0.14171 for welding speed and 0.08436 for axial force. By comparing these values, the most active variable influencing quality attributes is ascertained. The correlation will provide the degree of importance over the various quality characteristics of the input process control variables. Here, the maximum value of 0.2756 indicates that the tool rotational speed has the biggest impact among the other process control variables on the quality characteristics [7]. The plot graphically assesses the impact of each input welding parameter on the efficiency of the weld. Based on the main effect plot, input parameters such as tool profile, rotational speed and welding speed are found to be important as they reach their center point, while their lower and higher levels have not affected the consistency of the FS-welded specimens significantly. But the tilt angle of the FSW tool is considered important when it is between the middle and the higher level [8]. The interactions between the rotational speed of the tool and the shoulder base angle closely, it becomes clear that the impact of the shoulder base angle on the UTS depends on the rotational speed of the tool. If the tool rotates at 1250 rpm, the strength is minimized at 5°, however, at 1000 rpm the shoulder base angle yields the maximum strength at 5°. The shoulder base angle and rotational speed have a more significant impact on the surface hardness compared to other interactions [9]. Among the numerous common evolutionary algorithms, the Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) is widely adopted as an effective method for improving product quality in all manufacturing activities such as machining, shaping, and welding. NSGA – II uses random genetic operations to scan a whole design space for global optimum operation through different design points [10]. The mean absolute percentage error (MAPE) is applied to conduct error analysis of the implemented decision-making processes used in this report. To do this, 30 separate computer code runs were performed, and a final solution was obtained for each trial using the Shannon entropy and decision-making methods of TOPSIS. The value of each target (ultimate tensile power, elongation, and minimum hardness in the HAZ zone) were then equated with the better solutions obtained by each method after 30 runs [11]. The optimal setting of process parameter represents the relationship between the reference sequence and objective sequence, therefore greater fuzzy grey relational grade reveals the objective sequence has a stronger relationship than the reference sequence. Accordingly, the optimal setting of process parameters is larger fuzzy – GRG is desirable for obtaining larger UTS and TE of fabricated FS welded specimen. The FS welded joints made from square pin had the strongest Fuzzy GRG. Since flat-faced Pin profiles are correlated with eccentric material flow. This eccentricity of material flow allows for the movement of an incompressible material flow across the pin profile. The interaction between the static volume and the dynamic volume

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

determines the direction from the leading edge to the trailing edge of the revolving tool for the distribution of fleshy material [12].

2 Materials and Methods

The materials utilized for this examination are aluminum amalgams AA6101 and AA7075. With the help of a power hacksaw machine the rolled plates of 6mm in thickness were sliced into the essential size (100mm x 50 mm x 6 mm) and squaring the butting faces with the help of the milling process. Before the FS welding process butting edges of the weld specimens were cleaned by using a wire brush. Weld edges to be welded were additionally arranged with the goals that are completely parallel to one another. This is to ensure that between the plates there is no uneven hole that may not give good properties welded joints. In addition, surface arrangement was also performed in such a way that the surfaces of both plates are of equivalent size and balance. The compound structure in terms of weight rate tabulated in Table 1 and Mechanical properties of the base metals employed in this investigation at atmospheric condition is recorded in Table.2.

Table I Chemical Compounds (wt %) of parent metals

Element	Al	Si	Fe	Cu	Mg	Mn	Zn	Ti	Cr
AA6101	95	0.8	0.7	0.4	1.2	0.15	0.25	0.15	0.35
AA7075	87.5	0.4	0.5	2.0	2.9	0.3	6.1	0.2	0.28

Table II Mechanical behaviors of parent metals

Element	UTS (MPa)	YS (MPa)	% of Elongation	Hardness
AA6101	135	118	19	70
AA7075	622	573	10	195

3 Design of Experiments

Design of Experiments (DOE) is a formal, coordinated method for determining the relationship between factors that influence a process and the performance of that process. The three operation control variables of FS welding are considered factors of control. They are tool TRS, WS, and AF. Each variable has 3 different pitches like high, medium and low represented by 3, 2 and 1 respectively. If three operation control variables and 3 pitches for each L9 orthogonal array parameters should be used for conducting tests, based on the Taguchi method. FS welding operating variables and their levels take in to account for the conducting tests is presented in Table 3

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

Table III Process control variables and Levels

Process Control Variables	Levels		
	1	**2**	**3**
TRS (rpm) – A	1000	1100	1200
WS (mm/min) – B	30	45	60
AF (kN) – C	4	5	6

4 Experimentation

The Friction Stir Welding (FSW) Machine setup is shown in Figure 1. In this work Butt welding of AA7075 and AA6101 dissimilar alloy materials is carried out at by varying the process parameters. For welding, AA7075 was cut to dimension of 100*50*6 mm and AA6101 alloy was cut to dimension of 100*50*6 mm. 9 samples of AA7075 and AA6101 plates were cut as per the required dimensions. The plates are positioned and firmly clamped with help of backing plates to avert separation of the attached butting edges. The forces are fairly large during the tool's initial plunge and additional alerts are needed to verify that the plates are not separated in a butt arrangement. The tool mounted in tool holder with tilt angle 1.5° and the tool pin was throwing to a predestined deepness at the edges of the butting surface of the plates to be joined. The tool was transverse forward after residing time at the end of which the joint was formed by a single pass. After the weld is finished, the tool is taken back, left an opening at the end.

Figure 1. Friction stir welding machine

4.1 Process Response Measurement

The tensile behavior of FS welded joints was determined using the UTM (Make: FIE & Model: UTN 40). The trail samples were sliced from the fabricated joints and according to ASTM E8 dimension machined exposed in Figure 2. Three identical specimens were tested to acquire the average tensile strength value. The graphic image of the FS welded joint specimens after tensile fracture is exposed in Figure 3.

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

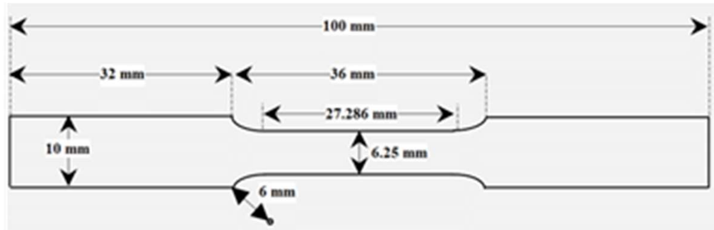

Figure 2 ASTM E8 Standard Tensile test specimen

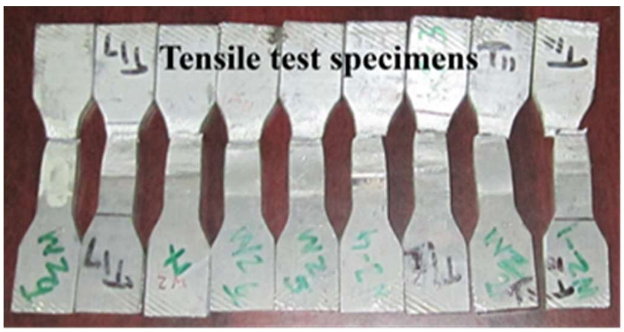

Figure 3 Tensile test specimen after fracture

The impact toughness was measured using pendulum type impact test machine (Make: FIE & Model: IT 30 ASTM). The three specimens were extracted across the weld line from friction stir welded joints and machined as per ASTM E23 standard size displayed in Figure 4. FS welded joint specimens fractured realistic images after charpy test are exposed in Figure 5.

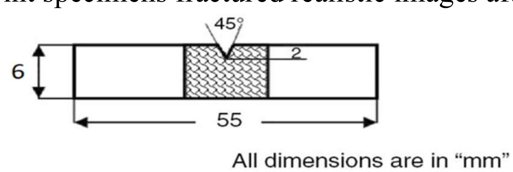

Figure 4. ASTM E23 Impact test specimen

Figure 5. Impact test specimen after fracture

Table 4 shows the L27 orthogonal array along with the experimental results of ultimate tensile strength, yield strength, percentage of elongation and impact strength of welded joint.

Table IV Taguchi's L27 Orthogonal Array with Experimental Results

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

Trial	Tool Rotational Speed (rpm)	Axial Force (KN)	Welding Speed (mm/min)	Tensile Strength (Mpa)	Yield Strength (Mpa)	% of Elongation	Impact Strength (joules)
1	1000	4	30	120.24	112.76	18.46	17
2	1000	4	45	119.45	111.68	17.45	18
3	1000	4	60	116.64	110.64	14.24	16
4	1000	5	30	121.1	113.47	19.14	16
5	1000	5	45	120.18	112.21	18.21	16
6	1000	5	60	119.28	110.49	17.42	17
7	1000	6	30	116.73	107.5	14.21	17
8	1000	6	45	116.52	106.51	14.71	16
9	1000	6	60	114.72	104.23	14	16
10	1100	4	30	128.76	122.41	24.18	23
11	1100	4	45	126.37	121.31	23.46	21
12	1100	4	60	125.23	119.02	21.42	21
13	1100	5	30	128.42	121.98	24.21	23
14	1100	5	45	127.65	120.46	22.61	20
15	1100	5	60	124.02	119.37	20.41	19
16	1100	6	30	126.42	119.54	18.62	20
17	1100	6	45	126.21	121.03	23.33	19
18	1100	6	60	123.12	117.65	21.46	19
19	1200	4	30	124.68	118.2	21.42	18
20	1200	4	45	124.2	117.56	20.33	18
21	1200	4	60	122.16	116.7	20.14	18
22	1200	5	30	125.46	119.45	23.42	19
23	1200	5	45	123.76	116.98	21.46	18
24	1200	5	60	121.78	116.42	19.33	18
25	1200	6	30	124.24	118.61	22.16	17
26	1200	6	45	122.78	116.23	20.15	18
27	1200	6	60	123.04	116.78	21.68	16

5 Results and Discussions

5.1 Grey-Taguchi Technique

In this work, Grey-Taguchi technique was employed for finding of better combination of process control variables to connect AA7075 and AA6101 alloy materials in friction stir welding method. Grey-Taguchi method is one of the best practices for multi objective optimization problems. Generally, Taguchi method is supportive for planning of experiments and finding of optimal setting individually for each output response, but in the present research

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

there are different output responses tensile properties and impact strength. There is necessity to find out the supreme combination of process control variables for all the output responses simultaneously. The step by step procedure in Grey-Taguchi technique is shown in Fig. 6.

Procedure of the Grey-Taguchi technique

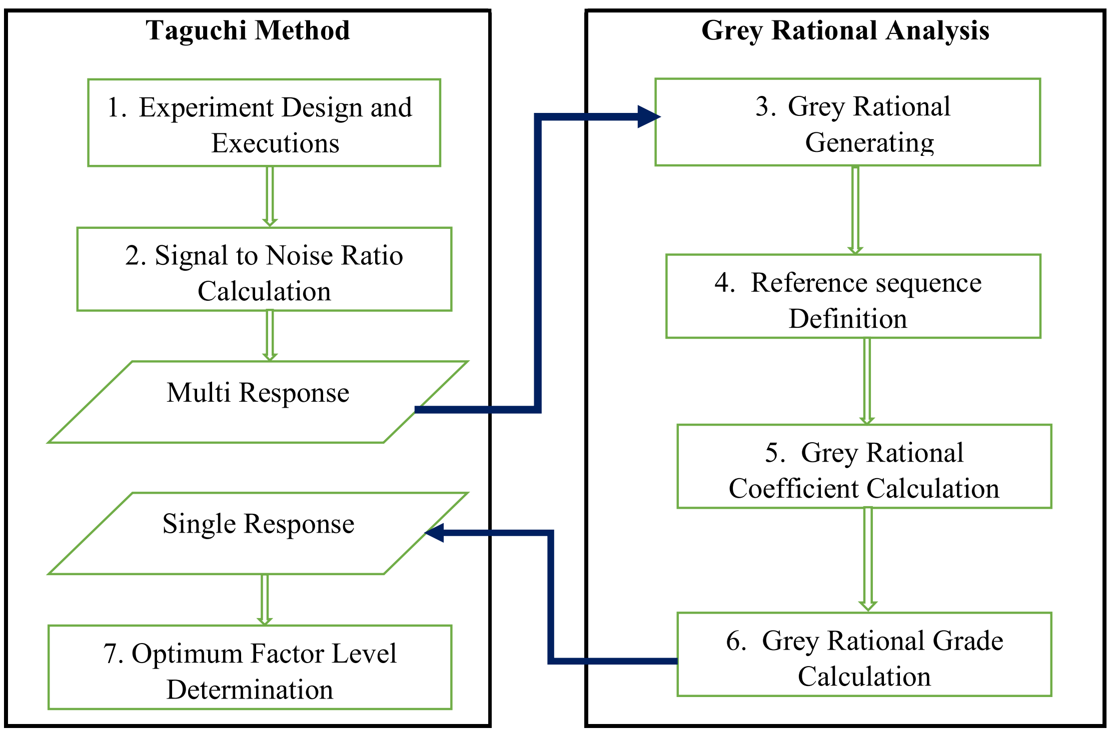

Figure 6. Procedure of the Grey-Taguchi Technique

5.2 Normalization of Experimental Results

In the Grey-Taguchi test the initial step is to normalize the experimental results of tensile properties and impact strength. Each output response value in the 0 to 1. range is normalized. For normalizing tensile properties (ultimate tensile strength, yield strength, % of elongation) and impact strength 'Higher-the-better' (Equ. 1) criterion is used. The normalized data for tensile properties and impact strength is given in Table 5.

$$X_j(k) = \frac{y_j(k) - \min\ _j(k)}{\max y_j(k) - \min y_j(k)} \qquad (1)$$

Where, Xj (k) = value after normalizing data/Grey relational generation value, min $y_j(k)$ = smallest value of $y_j(k)$ for k^{th} response, max $y_j(k)$ = largest value of $y_j(k)$ for k^{th} response.

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

Table V. Normalized data for UTS, YS, % of elongation and impact strength

Trials	Normalization Values			
	Tensile Strength (Mpa)	Yield Strength (Mpa)	% of Elongation	Impact Strength (joules)
1	0.39316	0.4692	0.43683	0.21429
2	0.33689	0.40979	0.3379	0.35714
3	0.13675	0.35259	0.02351	0.07143
4	0.45442	0.50825	0.50343	0.07143
5	0.38889	0.43894	0.41234	0.07143
6	0.32479	0.34433	0.33497	0.21429
7	0.14316	0.17987	0.02057	0.14286
8	0.12821	0.12541	0.06954	0
9	0	0	0	0.07143
10	1	1	0.99706	1
11	0.82977	0.93949	0.92654	0.78571
12	0.74858	0.81353	0.72674	0.71429
13	0.97578	0.97635	1	1
14	0.92094	0.89274	0.84329	0.57143
15	0.66239	0.83278	0.62782	0.5
16	0.83333	0.84213	0.4525	0.64286
17	0.81838	0.92409	0.91381	0.5
18	0.59829	0.73817	0.73066	0.42857
19	0.7094	0.76843	0.72674	0.35714
20	0.67521	0.73322	0.61998	0.35714
21	0.52991	0.68592	0.60137	0.28571
22	0.76496	0.83718	0.92262	0.42857
23	0.64387	0.70132	0.73066	0.28571
24	0.50285	0.67052	0.52204	0.35714
25	0.67806	0.79098	0.79922	0.21429
26	0.57407	0.66007	0.60235	0.35714
27	0.59259	0.69032	0.7522	0.07143

5.3 Grey Relational Coefficient

Once calculate normalizing the results of tensile properties like ultimate tensile strength, yield strength, % of elongation and impact strength, the next step is estimation of grey relational coefficient values for tensile properties and impact strength. The grey relational coefficient εj (k) can be estimated by using Equ. (2). the grey relational coefficient values for tensile properties and impact strength are given in Table 6.

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

$\varepsilon_j\,(k) = \frac{\Delta_{min}+\varphi\Delta_{max}}{\Delta_{oj}(k)+\varphi\Delta_{max}}$ (2)

Where, $\Delta oj\ (v)$ = Xoj(v) – X j (v), Δmax = larger value of Δoj, Δmin = smaller value of Δoj, Xj (v) = value after normalizing data/Grey relational generation value, Xoj(v) = Ideal value = 1 and in general assumed φ=0.5.

Table VI. Grey Rational Coefficient for UTS, YS, % of elongation and impact strength

Trials	Grey Rational Coefficient Values			
	Tensile Strength (Mpa)	Yield Strength (Mpa)	% of Elongation	Impact Strength (joules)
1	0.45174	0.48506	0.47029	0.38889
2	0.42988	0.45863	0.43026	0.4375
3	0.36677	0.43576	0.33864	0.35
4	0.4782	0.50416	0.50172	0.35
5	0.45	0.47123	0.4597	0.35
6	0.42545	0.43265	0.42917	0.38889
7	0.3685	0.37875	0.33797	0.36842
8	0.36449	0.36375	0.34954	0.33333
9	0.33333	0.33333	0.33333	0.35
10	1	1	0.99416	1
11	0.74601	0.89205	0.8719	0.7
12	0.6654	0.72837	0.64661	0.63636
13	0.9538	0.95483	1	1
14	0.86347	0.82337	0.76137	0.53846
15	0.59694	0.74938	0.57327	0.5
16	0.75	0.76003	0.47733	0.58333
17	0.73354	0.86819	0.85297	0.5
18	0.5545	0.65632	0.6499	0.46667
19	0.63243	0.68346	0.64661	0.4375
20	0.60622	0.65208	0.56817	0.4375
21	0.51542	0.61419	0.5564	0.41176
22	0.68023	0.75436	0.86599	0.46667
23	0.58403	0.62603	0.6499	0.41176
24	0.50143	0.60279	0.51127	0.4375
25	0.60832	0.7052	0.71349	0.38889
26	0.54	0.59528	0.55701	0.4375
27	0.55102	0.61753	0.66863	0.35

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

5.4 Grey Relational Grade (GRG) and Order

Grey relational grade (GRG) for each investigational run is the normal of grey relational coefficient value for a particular investigational run. GRG can be calculated by using Equ. (3). Larger value of grey relational grade specifies the top value, so highest grade value provides the higher order. The GRG and their position are given in Table 7. Fig. 12 shows the relational ship between experimental runs to the GRG.

$$\gamma_j = \frac{1}{n}\sum_{k=1}^{n} \varepsilon j\ (k) \qquad (3)$$

Where, n = No of process responses, εj (k) = Grey relational coefficient

Table VII. GRG and order

Trials	**GRG**	**RANK**
1	0.44899	20
2	0.43907	21
3	0.37279	24
4	0.45852	19
5	0.43273	22
6	0.41904	23
7	0.36341	25
8	0.35278	26
9	0.33750	27
10	**0.99854**	**1**
11	0.80249	3
12	0.66919	7
13	0.97716	2
14	0.74667	4
15	0.60490	9
16	0.64267	8
17	0.73868	5
18	0.58185	12
19	0.60000	11
20	0.56599	14
21	0.52444	17
22	0.69181	6
23	0.56793	13
24	0.51325	18
25	0.60397	10
26	0.53245	16
27	0.54679	15

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

5.6 Multi Objective Optimization

In order to investigate the significant control variables on tensile properties and impact strength. ANOVA was performed. ANOVA table for GRG are shown in Table 8. Since, it is shows that tool revolving speed has utmost dominating process control variables which is about 70.88% influence on grey relational grade and succeeding with transvers speed and axial force has effect on grey relational grade with contribution of 10.63% and 4.93%. The interaction effects of TRS x AF, TRS x WS, AF x WS on grey relational grade with contribution of 2.80, 4.70, 2.76 % respectively. Table 9 & Table 10 shows the response table for grey relational grade which gives the average of each process responses (Means and S/N ratio) for each level at each response. The ranks and delta values show that rotational speed have high effect on grey relational grade and is followed by transverse speed and axial force in that order.

Table VIII. Analysis of Variance for GRG

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**% Contribution**
TRS	2	0.54698	0.273489	85.94	0.000	70.88
AF	2	0.03805	0.019025	5.98	0.026	4.93
WS	2	0.08206	0.041029	12.89	0.003	10.63
TRS*AF	4	0.02160	0.005400	1.70	0.243	2.80
TRS*WS	4	0.03623	0.009058	2.85	0.097	4.70
AF*WS	4	0.02129	0.005323	1.67	0.248	2.76
Error	8	0.02546	0.003182			3.30
Total	26	0.77167				

Table IX. Response table for GRG (means)

Level	**TRS**	**AF**	**WS**
1	0.4028	0.6013	**0.6428**
2	**0.7513**	**0.6024**	0.5754
3	0.5718	0.5222	0.5078
Delta	0.3486	0.0802	0.1350
Rank	1	3	2

Table X. Response table for GRG (S/N ratio)

Level	**TRS**	**AF**	**WS**
1	-7.951	-4.786	-4.288
2	-2.632	-4.735	-5.099
3	-4.888	-5.950	-6.085

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

Delta	5.318	1.215	1.797
Rank	1	3	2

As grey relational grade 'higher the better' type response, it can be seen from Figure 7, that the third level of rotational speed, third level of force and first level of transvers speed offers extreme value of grey relational grade. Hence, Tool revolving speed is 1100 rpm, forces is at 4 KN and transvers speed of 30 mm/min is the finest combination of process control variables for obtaining utmost tensile properties and maximum impact strength simultaneously in FSW process. Figure 8 also suggest the same combination of process control variables.

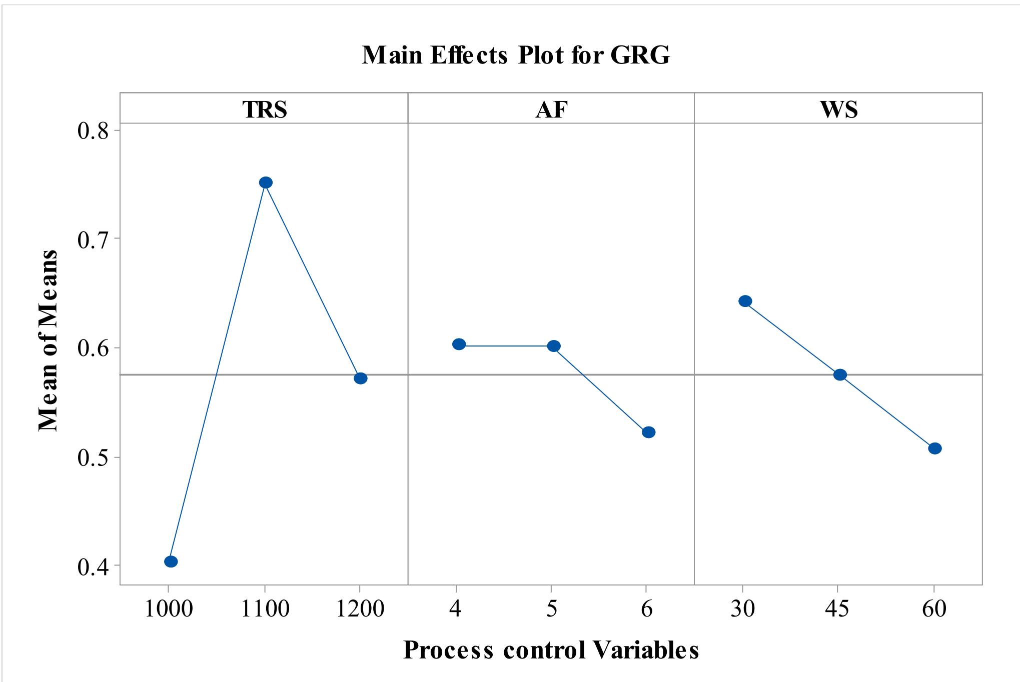

Figure 7. Main effect plot for GRG

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

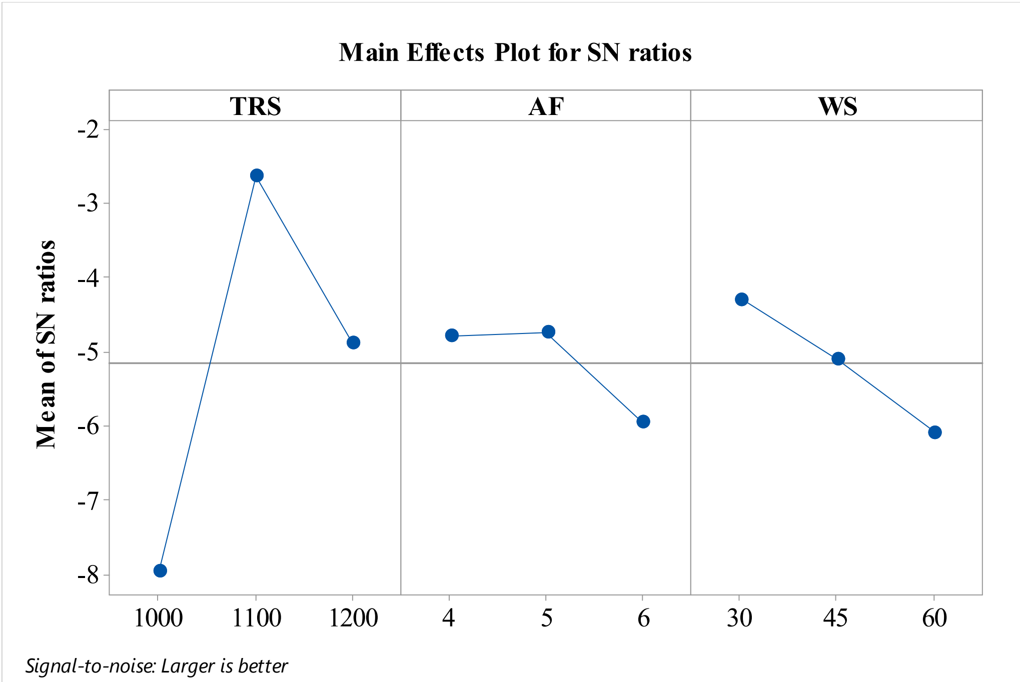

Figure 8. S/N Ratio for GRG

5.7 Anticipated optimum condition

Based on trials, the optimum level setting was found at tool revolving speed of 1100 rpm table transverse speed of 30 mm/min and axial force of 4 kN. So, the anticipated grey relation grade can be determined as:

$$\hat{\gamma} = \gamma_m + \sum_{k=1}^{n}(\hat{\gamma}_k - \gamma_m) \qquad (4)$$

Where γ_m is the total mean GRG, $\hat{\gamma}_k$ is the mean GRG at the optimum level, and n is the number of process control variables that affect the quality characteristics.

So, anticipated grey relation grade = 0.8067.

The validation experiment is not necessary here, as the optimized experiment at factor level now available within the planned trialing. The actual grade of gray relation at optimal condition is 0.9735; while the grade of gray relation expected is 0.8067. So; the gap is just 0.16 (approx.). This gap arises due to ignoring the nonlinear effects in three factor three level Taguchi L27 orthogonal array.

6 Conclusions

In this investigation, to find the optimum combination of friction stir welding process control variables to join AA7075 & AA6101 alloy materials, Taguchi based grey analysis was applied. The important conclusions from the present research work are summarized as follows:

A. The finest combination of process control variables for obtaining optimum ultimate tensile strength of 129 Mpa., maximum yield strength of 119.21Mpa, maximum % of

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

elongation 24.64% and impact strength 23 joules simultaneously in FSW process is found at Tool revolving speed is 1200 rpm, transvers speed of 30 mm/min and axial force is at 5 KN.

B. ANOVA results shows that process control variables too revolving speed shows major effect on the output responses in FSW process and axial force shows less influence on the output responses.

C. The current Gray Relationship Grade at the optimum condition is 0.9735, while the predicted Gray Relationship Grade is 0.8067. Thus, the difference is only 0.16 (approx.). This variation occurs due to the neglect of the nonlinear effects in the orthogonal 3-level Taguchi L27 array.

Reference

[1] W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Murch, P. Templesmith, C. J. Dawes. ‘Improvements to Friction Welding’, GB Patent Application No. 9125978.8., 1991.

[2] R. S. Mishra, ZY. Ma. Friction stir welding and processing. Material Science Engineering R50 2005, 1 – 78.

[3] K. E. Knipstrom, B. Pekkari. “Friction stir welding process goes commercial”, Welding Journal 1997 (76), No. 9, 55 – 57.

[4]. Mohammed Yunus and Mohammad S. Alsoufi, “Mathematical Modelling of a Friction Stir Welding Process to Predict the Joint Strength of Two Dissimilar Aluminium Alloys Using Experimental Data and Genetic Programming” Modelling and Simulation in Engineering, volume 2018.

[5] Srinivasa Rao Mallipudi, Ramanaiah Nallu, “Optimization of Process Parameters for FSW of Al-Mg-Mn-Sc-Zr Alloy Using CCD And RSM”, Journal of Mechanical Engineering, VOL 68 (2018), NO 3, 195 – 224.

[6] V. K. Parikh, A. D. Badgujar, N. D. Ghetiya, “Multi-Objective Optimization of FSW Process Parameter using MOORA method”, International Journal of advances in Production Aand Mechanical Engineering (IJAPME), VOL.-3,No-2, 2017, 19-24.

[7] Saurabh Kumar Gupta, K. N. Pandey and Rajneesh Kumar, “Multi-Objective Optimization of Friction Stir Welding of Aluminium Alloy Using Grey Relation Analysis with Entropy Measurement Method”, Nirma Univeristy Journal of Engineering and Technology Vol. 3, N0. 1, 2014, 29-34.

[8] Shanavas Shamsudeen, John Edwin Raja Dhas, “Optimization of Multiple Performance Characteristics of Friction Stir Welded Joint with Grey Relational Analysis”, Materials Research. Vol. 6, 2018, 1-13.

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/

[9] Sajjad Khaki, Ali Heidari, Amin Kolahdooz, "Optimizing Friction Stir Welding Process for Enhancing Strength and Hardness using Taguchi Multi-Objective Function Method", Int J Advanced Design and Manufacturing Technology, Vol. 12, No. 3, 2019, 25-33.

[10] D.Vijayan, P. Abhishek, "Multi Objective Process Parameters Optimization of Friction Stir Welding using NSGA – II", IOP Conf. Series: Materials Science and Engineering, vol.390, 2018, pp1-7.

[11] Mehran Tamjidy, B. T. Hang Tuah Baharudin, Shahla Paslar, Khamirul Amin Matori,Shamsuddin Sulaiman and Firouz Fadaeifard, "Multi-Objective Optimization of Friction Stir Welding Process Parameters of AA6061-T6 and AA7075-T6 Using a Biogeography Based Optimization Algorithm", (MDPI) Materials, Vol.10, 533, 2017, 1-19.

[12] D.Vijayan, V. Seshagiri Rao, "Optimization of friction stir welding process parameters using RSM based Grey–Fuzzy approach", Saudi Journal of Engineering and Technology, Vol-2, Iss-1, 2017, 2-25.

Copyright © 2022. Journal of Northeastern University. Licensed under the Creative Commons Attribution Non-commercial No Derivatives (by-nc-nd). Available at https://dbdxxb.cn/