

Effect of Process Parameter and Optimization of Friction Stir Welded Dissimilar Aluminium Alloy

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Abstract

The parametric analysis on friction stir welding of dissimilar aluminium alloys i.e. AA5083- AA1100 using different tool geometries were performed with experimentation. A multi response optimization problem was developed to perceive optimal process parameters to achieve better mechanical properties. Taguchi's L16 orthogonal array design and the signal to-noise ratio (S/N ratio) concept were selected to optimize the objective functions with the experimental results. The objective functions were chosen with respect to process parameters i.e. tool rotational speed, welding speed, tool shoulder diameter, and tool pin type. The Taguchi's approach followed by the Grey relational analysis was successfully applied to solve this multi-response optimization problem. The ANOVA method was used to evaluate the overall output of various factors considered and optimal results were confirmed with additional experiments. The current study obtained the application viability of the Grey Taguchi method for the continuous enhancement of the weld quality in the manufacturing sector.

Keywords: FSW, AA5083, AA1100, Orthogonal array, Signal-to-noise ratio, Taguchi approach.

INTRODUCTION

Friction stir welding (FSW) is a solid state joining process. The main advantages of the Solid state joining process are the retained base metal properties and no additional filler materials required to make a joint. Some of the example of solid state welding techniques are resistance welding, ultrasonic welding, diffusion welding, and friction stir welding etc. FSW is the most commonly accepted method for joining non-ferrous light weight materials and this process finds many applications in the aerospace, shipbuilding, and other transportation industries [1].

The FSW was invented in 1991 at The Welding Institute, UK [2]. Since then, many research articles reported on friction stir welding of aluminium alloys. Peel et al. [3] investigated the microstructure graphs of 3 mm AA 5083 welds produced using two different tool and varying the weld speed only. The residual stresses were also studied with the help of laser-based interferometric strain mapping technique (ESPI). The weld zone reported to be in tension in longitudinal and transverse directions of the plates. Similarly, the microstructure of 6.35 mm AA7075-T6 FSW was studied by Rhodes et al. [4].

Further, the micro structural study was also performed by Hou et al. [5] for an unequal shoulder self-reacting tool and studied the effect of rotational speed. Biswas and Mandal [6] studied the effect of process parameters on the FSW of marine grade AA5083 based on the mechanical properties of the welds.

A three dimensional transient thermal analysis was also performed [7] to study the effect of process parameter on the FSW of 6 mm thick AA1100 plates. Whereas, Chao and Xi [8] performed a thermo-mechanical analysis by decoupling the process and calculated the residual stresses. A boundary value problem was also formulated by Chao et al. [9] and solved using inverse analysis. Song and Kovacevic [10] also developed a heat source to study the thermal history of FSW joints.

In the microstructure and mechanical properties, the tool geometry plays a vital role. The material movement is directly linked to the tool geometry. So, Colegrove and Shercliff developed a trivex tool to study the material flow [11]. Similarly, different flow model were proposed using different tool geometries to study the effect

of tool geometries on the weldments [12], [13], [14], [15].

However, some researcher also worked in the area of the FSW process parameter optimisations like Elangovan et al. [16] proposed a mathematical model to perform the analysis and used analysis of variance (ANOVA) technique to find the best process parameter. Similarly, Jayaraman et al. [17] made use of Response Surface Methodology [17] and Artificial Neural Network to predict the tensile strength of the FSW joint. Mohanty et al. [18] also used Response Surface Methodology for tool designing and made use of Fuzzy logic and Artificial Neural Network [19] to predict the weldment characteristics and the effectiveness of the optimization technique. Few contributions on FSW tool material and design [7, 17, 20-23]. All these efforts brought friction stir welding process in further enhancement but many research articles are focussed on FSW of similar metals.

FSW of dissimilar metals, Topic et al. [24] reported on FSW of dissimilar aluminium alloys AA1050 to AA6016 and they concentrated on measuring the weld quality by the micro structural examination and

hardness measurements. Tehyo et al. [25] worked on joining dissimilar combination metals i.e. AA6061 to a semisolid metal 356 and reported the tensile and hardness properties of the welds. Palanivel and Koshymathews [26] predicted optimized process parameter of friction stir welded AA5083 using response surface method. Decent amount of publications are reported on mechanical and microstructural study of FSW on dissimilar metals joining [27-31].

In this study, the optimisation of process parameters for friction stir welding of AA1100 to AA5083 is reported using Grey Taguchi optimisation technique. Detailed experimentation and investigations has been performed to correlate all the welding parameters (i.e. Tool Rotational Speed, Welding Speed, Tool Shoulder diameter, Tool Shoulder diameter, Tool Pin Type) with the weld quality achieved. The weld strength is checked for each experiment by preparing the test samples. For measuring the temperature K-Type thermocouples are used on both advancing and retarding sides.

EXPERIMENTAL CONDITIONS AND PROCESS PARAMETERS

A modified vertical milling machine is used to perform all the FSW experiment. A data

acquisition system along with K-type thermocouples is used for the temperature measurement, shown in Fig. 1. The SS310 material is used to fabricate the FSW tools

used in the analysis. The different tool used for performing the experiment is shown in Fig. 2.

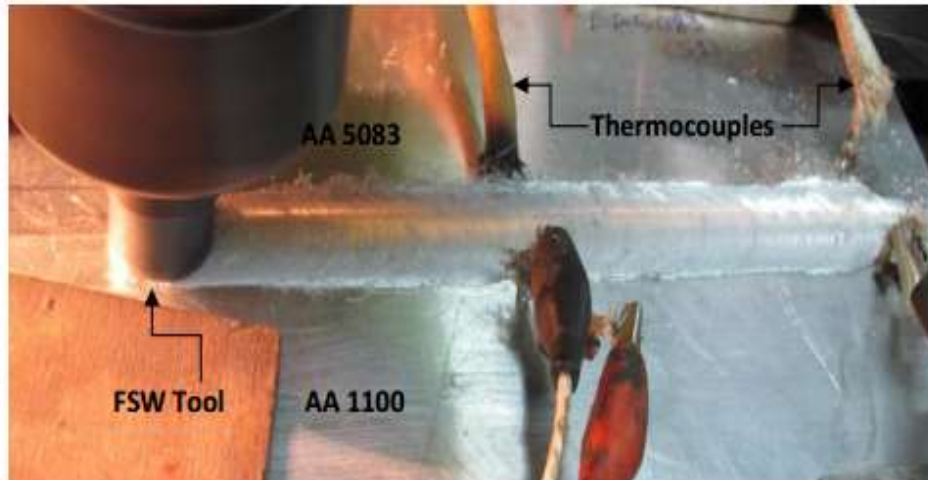


Fig.1 Experimental Set up

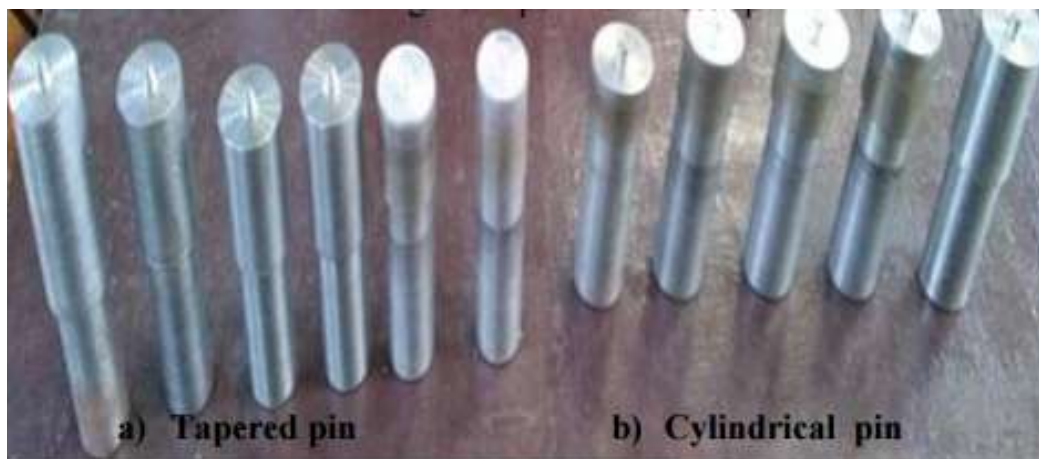


Fig. 2. Fabricated FSW tools

The thermocouples are placed in 3 mm deep holes which were at 16 mm away from the

centre of the weld line on both sides. Two dissimilar metals i.e. AA1100 and AA5083

are used as the base material in all the experiment. The dimensions of the specimens are 200 mm length, 100 mm

width, and 6 mm thickness. The chemical compositions of both the materials are shown in the Fig. 3.

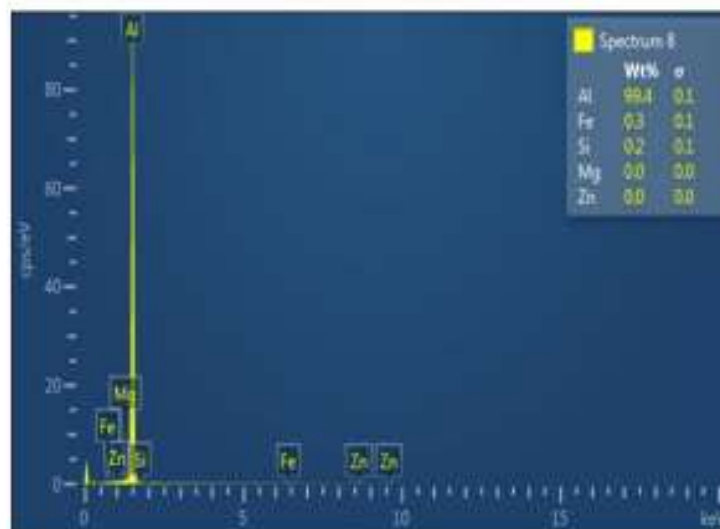


Fig.3. Chemical Composition of base materials a) AA1100



Fig.3. Chemical Composition of base materials b) AA5083

The chemical compositions of the two materials are checked using Energy-

dispersive X-ray spectroscopy (EDX) which shows large peak of Aluminum i.e. about

99.4 % for AA1100 whereas, for AA5083 along with Aluminum, Mg peak is also obtained which is found to be 3.1% shown in Fig. 3. The two samples of the both the materials have prepared to test the tensile strength of the material in Universal Testing Machine (UTM). The four important process parameters and with four levels are considered for the present study shown in Table 1.

Taguchi's Design of experiments (DOE) are performed using the above parameters. Mixed level design are selected i.e. four levels for three parameters and Two levels for one parameter, as shown in Table 1. Sixteen number experiments are conducted using the Taguchi's DOE approach shown in the Table 2.

Table 1 Process parameters and their limits

Parameters	Notation	Unit	Levels of Factors			
			1	2	3	4
Tool Rotational Speed	TRS	rpm	600	815	1000	1500
Welding Speed	WS	mm/sec	36	63	98	132
Tool Shoulder diameter	SD	mm	24	26	28	30
Tool Pin Type	TP	--	CYL		TC	

Table 2 Taguchi's L16 orthogonal array design

S.No	TRS	WS	SD	TP
1	600	36	24	CYL
2	600	63	26	CYL
3	600	98	28	TC
4	600	132	30	TC
5	815	36	26	TC
6	815	63	24	TC
7	815	98	30	CYL
8	815	132	28	CYL
9	1100	36	28	CYL
10	1100	63	30	CYL
11	1100	98	24	TC
12	1100	132	26	TC
13	1500	36	30	TC
14	1500	63	28	TC
15	1500	98	26	CYL
16	1500	132	24	CYL

The Experiments are successfully completed with healthy weld. The defect free welds are obtained in all the cases. The samples are taken from the centre of the welded plates and tensile strength is tested in UTM. The test are conducted on sample and it is found that the breaking of all the test samples are away to the welding zone i.e. between heat affected zone and base

material of AA1100 as shown in Fig. 4. The specimens are machined by milling machine according to the ASTM E-8 standards. The tensile strength along with the elongation of the base materials is reported in Table 3. The tensile strength, elongation and peak temperature of all the Taguchi's designed experiments is shown in Table 4.

Table 3 Mechanical properties of AA1100 and AA5083

Material	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
Base Material (AA1100 H-16)	138	155	6
Base Material (AA5083)	170	235	16



Fig. 4. Tensile test samples

Table 4 Experimental data

S.No	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Peak Temp (⁰ C)
1	107.5	127.2	14.1	322.5
2	118	140.1	14.5	321.8
3	116.8	138.8	15.2	332.1
4	113.5	139.6	14.7	324.3
5	118.7	150.2	15.1	334.6
6	120.1	157.5	16.2	322.8
7	115.9	142.9	15.3	333.5
8	119.8	139.8	14.8	328.9
9	121.3	140.8	14.2	341.1
10	119.8	145.2	15.4	341.8
11	122.1	150.4	16.2	333.5
12	117.2	141.5	14.2	324.1
13	115.4	144.1	15.4	346.2
14	118.8	139.9	14.8	338.7
15	116.2	143.2	14.3	330.8
16	109.9	138.5	13.9	328.4

The maximum peak temperature is obtained in case of cylindrical pin with highest rotational speed, Shoulder diameter and lowest welding speed. Whereas, the lowest peak temperature is also obtained with cylindrical pin geometry and lowest tool rotational speed. However, the maximum elongation is obtained in case of taper pin geometry while the minimum elongation obtained with cylindrical pin geometry. The highest yield strength and ultimate strength is obtained for taper geometry at 1100 and 815 rpm respectively with 24 mm shoulder diameter.

PARAMETRIC OPTIMISATION OF FSW OF AA1100-AA5083

Dr. Genichi Taguchi developed a method based on orthogonal arrays experiment to predict the optimal process parameters. Orthogonal array provide a set of coordinated (least possible experimental paths) experiments. Whereas, Taguchi's signal-to-noise ratios (S/N ratio) gives logarithmic functions of desired outputs assist as objective functions for optimization. The S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). The standard S/N ratios generally used are as: Nominal is best (NB), lower the better (LB) and higher the better (HB). The

optimal setting is the parameter combination, which has the highest S/N ratio.

The normalisation of output data, called as grey relational generation (GRG) i.e. all the measured experimental output characteristics are normalized ranging zero to one. The normalised of Yeild Strength, Ultimate Tensile Strength, % Elongation, Peak Temperature corresponding to higher-the-better criterion is expressed as

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$$

where $x_i(k)$ is the value after the Grey relational generation, $\min y_i(k)$ is the smallest value of $y_i(k)$ for the k th response, and $\max y_i(k)$ is the largest value of $y_i(k)$ for the k th response. The normalized output data after Grey relational generation are tabulated in Table 5.

Table 5 Normalisation of output data (Grey relational generation)

S.No	Yeild Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Peak Temp ($^{\circ}$ C)
1	0	0	0.086957	0.028688525
2	0.719178082	0.425742574	0.26087	0
3	0.636986301	0.382838284	0.565217	0.422131148
4	0.410958904	0.409240924	0.347826	0.102459016
5	0.767123288	0.759075908	0.521739	0.524590164
6	0.863013699	1	1	0.040983607
7	0.575342466	0.518151815	0.608696	0.479508197
8	0.842465753	0.415841584	0.391304	0.290983607
9	0.945205479	0.448844884	0.130435	0.790983607
10	0.842465753	0.594059406	0.652174	0.819672131
11	1	0.765676568	1	0.479508197
12	0.664383562	0.471947195	0.130435	0.094262295
13	0.54109589	0.557755776	0.652174	1
14	0.773972603	0.419141914	0.391304	0.692622951
15	0.595890411	0.528052805	0.173913	0.368852459
16	0.164383562	0.372937294	0	0.270491803

Table 6 Evaluation of $\Delta 0_i$ for each of the responses

S.No	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Peak Temp ($^{\circ}$ C)
1	1	1	0.913043	0.971311
2	0.280822	0.574257	0.73913	1
3	0.363014	0.617162	0.434783	0.577869
4	0.589041	0.590759	0.652174	0.897541
5	0.232877	0.240924	0.478261	0.47541
6	0.136986	0	0	0.959016
7	0.424658	0.481848	0.391304	0.520492
8	0.157534	0.584158	0.608696	0.709016
9	0.054795	0.551155	0.869565	0.209016
10	0.157534	0.405941	0.347826	0.180328
11	0	0.234323	0	0.520492
12	0.335616	0.528053	0.869565	0.905738
13	0.458904	0.442244	0.347826	0
14	0.226027	0.580858	0.608696	0.307377
15	0.40411	0.471947	0.826087	0.631148
16	0.835616	0.627063	1	0.729508

Grey relational coefficient (GRC) i.e. the correlation between the desired and actual experimental output data is calculated as:

$$\xi_i(k) = \frac{\Delta_{min} + \Psi \Delta_{max}}{\Delta_{0i}(k) + \Psi \Delta_{max}}$$

Where $\Delta_{0i}(k) = \|x_0(k) - x_i(k)\|$ = difference of absolute value $x_0(k)$ and $x_i(k)$; Ψ is the distinguishing coefficient $0 \leq \Psi \leq 1$;

$$\Delta_{min} = \min_{i \in \{1, 2, \dots, n\}} \Delta_{0i}(k)$$

the smallest value of Δ_{0i} , and

$$\Delta_{max} = \max_{i \in \{1, 2, \dots, n\}} \Delta_{0i}(k)$$

largest value of Δ_{0i} . The grey relational grade is given by the average of all grey relational coefficients corresponding to the selected responses. Thus, the multi response problem is converted into a single response optimisation problem. Further, The grey relational grade (ω) is calculated by averaging the grey relational coefficient, as

$$\Omega_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k)$$

Where, n = no of process responses.

The best process sequence is given by the utmost value of grey relational grade. Grey relational coefficient of each performance characteristics is shown in Table 7 where the value for Ψ is taken as 0.5.

The optimal experiment which contains the optimum output data is represented by the

maximum value in the grey relational grade Shown in Table 8. The maximum value in the grey relational grade is obtained as 0.825529 for the experiment no 6. Therefore, the optimal process parameters for the maximum grey relational grade are obtained as TRS: 815 rpm, WS: 63mm/min, TD: 24 mm, TP: TC.

Table 7: Grey relational coefficients of each performance characteristics

S.No	Yeild Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Peak Temp ($^{\circ}$ C)
1	0.333333	0.333333	0.353846	0.339833
2	0.640351	0.465438	0.403509	0.333333
3	0.579365	0.447563	0.534884	0.463878
4	0.459119	0.458396	0.433962	0.357771
5	0.682243	0.674833	0.511111	0.512605
6	0.784946	1	1	0.342697
7	0.540741	0.509244	0.560976	0.48996
8	0.760417	0.461187	0.45098	0.413559
9	0.901235	0.475667	0.365079	0.705202
10	0.760417	0.551913	0.589744	0.73494
11	1	0.680899	1	0.48996
12	0.598361	0.486356	0.365079	0.355685
13	0.521429	0.530648	0.589744	1
14	0.688679	0.462595	0.45098	0.619289
15	0.55303	0.514431	0.377049	0.442029
16	0.374359	0.443631	0.333333	0.406667

The effect of the parameters for overall grey relational grade is shown in Fig 5. The analysis of variance using adjusted SS for tests is given by Table 9. It is found that the

most influencing process parameter within the considered overall parameters is tool rotational speed (TRS) is about 37.5% and welding speed (WS) is about 23%. As there

is huge difference in the physical properties of the chosen materials, the residual error obtained about 16%.

Table 8 Grey relational grades

Experiment No	Grey relational grade
1	0.338736
2	0.461765
3	0.494558
4	0.43378
5	0.61191
6	0.825529
7	0.52213
8	0.509159
9	0.584709
10	0.637951
11	0.771345
12	0.458494
13	0.634437
14	0.536888
15	0.480053
16	0.400412

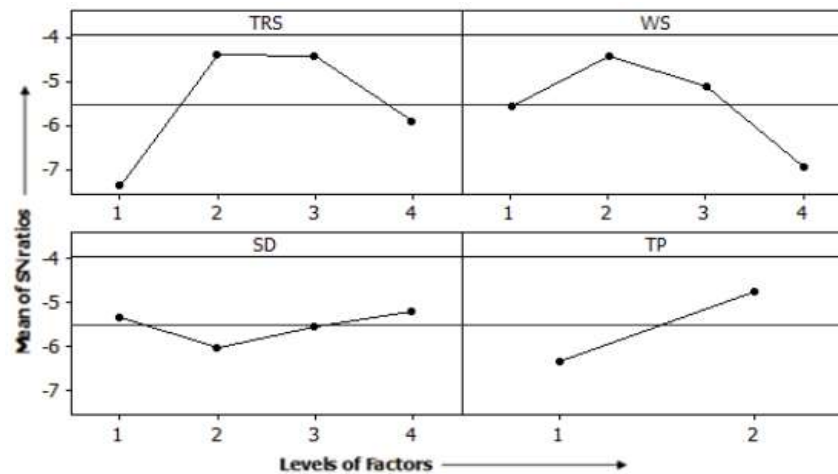


Fig. 5. Main effect plots for overall Grey relational grade

Table 9 Analysis of variance using adjusted SS for tests

Parameter	% Contribution
TRS	37.53131586
WS	22.90532
SD	5.738259
Tool pin type	17.20682
Residual Error	16.61828
Total	100

It is found that the optimal results is provided by the experiment no 6 (i.e. TRS: 815 rpm, WS: 63mm/min, TD: 24 mm, TP: TC) among experiments. Hence, some of

the mechanical studies are reported for the sample of experiment no 6. The Fractograph of FSW sample no 6 is Shown in Fig. 6.

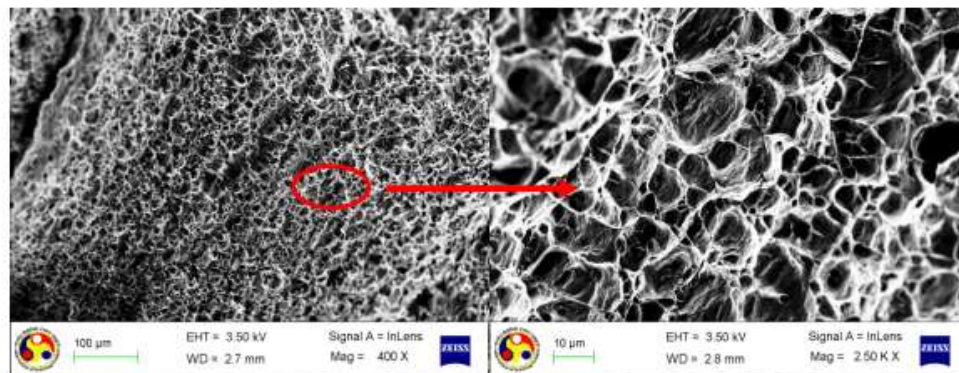


Fig. 6 FESEM analysis of fractograph of FSW samples no 6. a) Mag 400X b) Mag 2.5KX

The fracture surface of the FSW sample no 6 is studied using field emission scanning electron microscope (FESEM) at 400X and 2500X. The fractured surface of the samples is appeared to have uniform dimples around the nodule. These dimples are occurred due to the formation of micro-voids and

coalescence phenomena, when specimen is under uniaxial tensile loading.

CONCLUSION

- The comprehensive methodology of Taguchi optimization technique combined with the Grey relational

analysis was successfully applied and reported for evaluating optimal process parametric combination of friction stir welding on dissimilar aluminum alloys.

- The correlations between the most significant parameters and the mechanical properties and heat output of the FSW process using grey Taguchi technique was Established.
- The numbers of experiments performed were minimised using the most effective Taguchi optimisation technique. The most important criteria was that the joint strength should not be lesser than the weakest of the given combination in dissimilar metal FSW joint.
- The maximum value in the grey relational grade represented the optimal experiment that contained the optimum output data. The maximum obtained value in the grey relational grade is 0.825529 for the experiment no 6. Therefore, the optimal process parameters obtained for the maximum grey relational grade are

TRS: 815 rpm, WS: 63mm/min, TD: 24 mm, TP: TC.

- Quality assessment of FSW joints by the tensile behaviour revealed that the tapered cylindrical pin tool perfectly suits for the successful welding of two dissimilar combination of alluminium (i.e. AA1100 to AA5083). It was also seen that the most influencing process parameter was tool rotational speed and welding speed which had the impact of 37.5% and 23%.

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