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Design and optimization of the process parameters for friction stir welding of dissimilar aluminium alloys

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Abstract

Friction Stir Welding (FSW) is one of the unique solid state welding technique that is fast gaining importance because of its ability to produce strong joints. The friction stir welding technique is effectively used in this research to join 5 mm thick dissimilar aluminium alloys of AA 7075-O and AA 5052-O grade. The effect of tool pin profile and tool rotational speed on the mechanical properties like micro-hardness and tensile strength are studied by the optimized Design of Experiments (DOE). The experiments are designed based on L16 orthogonal array considering TAGUCHI techniques for four design parameters and four parametric levels. The outcomes of experimental techniques are tabulated and TAGUCHI analysis, Analysis of Variance (ANOVA) are carried out in Minitab software. From the experimental results and statistical techniques, the methodology is validated and the outcomes of the experiments are found to be in close agreement with the statistical results with the error less than 5% of the mean difference value. The optimized process parameters for better micro hardness are as follows: tool rotational speed of 1200 rpm, feed of 120 mm/min, tool offset of 1 mm, and cylindrical tapered pin tool profile; while the optimized design of process parameters for better tensile strength are as follows: tool rotational speed of 1400 rpm, feed of 120 mm/min, tool offset of 1 mm and cylindrical tapered pin profile. The design and optimization of the process parameters for friction stir welding of dissimilar aluminium alloys is necessary for high strength weld joints.

Keywords: Design, Optimization, Friction, Stir, Welding, Aluminium

1. Introduction

Friction stir welding is the solid state welding process, in which the joining of workpieces can be effectively done by using non consumable tool, which helps to soften the metal by generating a heat due to friction between rotating tool and workpieces [1-4]. When the tool is rotating inside the workpieces, it will plastically deform the material and result in a strong joint. The process is fast gaining significance in welding of aluminium and its alloys, especially in aerospace and automobile components.

The research findings from the latest works on friction stir welding have concentrated on the development of process methodologies and this involves the evolution of the techniques [5, 6]. The Friction Stir Welding process is a procedure of strong state joining that was concocted by “The Welding Institute” in the late nineties [7]. It is a consistent procedure involving the plunging of the tool on to the butting countenances of a joint [8, 9]. The relative movement between the substrate and the device produces frictional heat making a plasticized zone around the tool-work interface [10]. This procedure utilizes a non-consumable pivoting tool which comprises of a pin that stretches out under a shoulder which is constrained into the nearby mating edges [11, 12].

FSW process is obviously appropriate for welding of divergent aluminum alloys. Since these procedures do not include the process of melting, the issue of weld distortion doesn't emerge. Likewise, FSW process overcomes an array of different issues in combination welding of aluminum composites, for example, porosity, distortion, heat affected zones and cracking [13]. FSW of Aluminum Alloys of two diverse combinations welded with explicit equipment arrangements are extensively studied by several researchers [14-17]. The researches focuses on the portrayals of the mechanical and metallurgical properties with the above unique blend to assess the characteristics and qualities of the welded joints and results construed [18-21].

AA 7xxx and AA 5xxx are light metal alloys which are most commonly used in various structural applications, especially in the field of aerospace, marine and automobile industries. When these materials are used to fabricate different structural components, the total weight will be decreased and it ultimately leads to the increase in the fuel efficiency and reduction in the environmental pollution [22-24]. The joining of dissimilar aluminium alloys by using conventional fusion welding technique results in the formation of intermetallic compounds and various welding related defects due to the generation of high temperature [25, 26]. Formation of solidification cracks in the aluminium alloy is a common defect in fusion welding of

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aluminium alloys due to variation in the weld metal composition [27, 28]. The composition of base metal, filler metal and the amount of dilution is very important to reduce the formation of solidification cracking, Henceforth, FSW process can provide the solutions to these types of defects [29, 30]. Further, the process parameters have a major effect on the outcomes of the results in the FSW process. The design and optimization of the process parameters for friction stir welding of dissimilar aluminium alloys has led to better process control and thereby extended its scope for the use of the optimized process parameters for friction stir welding of dissimilar aluminium joints in real time engineering applications [31-34]. Thus, the present work is aimed at the optimization of the process parameters for friction stir welding by TAGUCHI and ANOVA techniques.

2. Materials and methods

2.1 Materials for workpieces

The process of friction stir welding is carried out on dissimilar alloys of aluminium, viz., annealed ('O' Temper designated) AA 7075 and AA 5052 plates to achieve maximum workability with increased toughness and ductility, the chemical composition of the alloys selected for the present work is given in Table 1. The workpieces are cut into a required size of 170 x 60 x 5 mm as shown in Figure 1, depending upon the available fixture dimensions, and in parlance with the findings of the available literature, and the FSW hand book [35]. The chemical composition of Aluminium AA 7075-O and Aluminium AA 5052-O Alloy is considered from the AZOM reference guide [36].

AA 7075-O, annealed aluminium alloy is selected for the present work, since it exhibits high strength, fracture toughness and resistance to corrosion which is the basic attribute for its use in aerospace structures. The modulus of elasticity for 7075 aluminum is 71.7 GPa, and it's shear modulus is 26.9 GPa. Generally, this alloy is strong and resists deformation well, which suits it for applications which need a tough-yet-light metal. Some major applications of aluminium AA 7075 include aircraft fittings, gears, shafts, missile parts, worm gears and aerospace components. While AA 5052-O is an annealed aluminium alloy having magnesium as the major alloying element with better strength, corrosion resistance and weldability. AA 5052-O aluminum alloy is stronger than other popular alloys with a modulus of elasticity of 70.3 GPa and shear modulus of 25.9 GPa and has an increased corrosion resistance. These characteristics allow 5052 aluminum alloy to excel in the marine industry as well as in electronics and chemical industries, with some of the typical applications being pressure vessels, electronic enclosures, electronic chassis, hydraulic tubes, medical equipment and hardware signs, that is the major factor for its selection in present work to optimize the process parameters of the FSW for plate structures especially having its wide scope in aerospace components [37]. Saeed et al., [38], have studied on the hardness of Aluminium AA 5052 and Aluminium AA 7075 alloys and have compared the base alloys with equal channel angular rolled plates and thereby concluded that the hardness of the rolled plates has increased with the number of passes.

2.2 Tool specifications

The friction stir welding is carried out by using a typical non consumable tool made up of H13 tool steel with a hardness of 55 HRC. The tool pin materials and dimensions are selected based on the thickness of the plate considered and the FSW hand book specifications [35]. The tool specifications are shown in Table 2. In the present research work, four pin profiles viz., cylindrical, cylindrical taper, square and triangular have been considered, the schematic of all the four pin profiles are given in Figure 2.

Table 1 Chemical composition of AA 7075-O and AA 5052-O alloy [36]

Alloy	Al	Zn	Mn	Si	Cu	Fe	Mg	Ti	Cr	Others
AA 7075	Bal.	5.8	0.2	0.4	1.6	0.4	2.4	0.1	0.25	0.14
AA 5052	Bal.	0.1	0.1	0.45	0.1	0.35	2.6	-	0.2	0.15

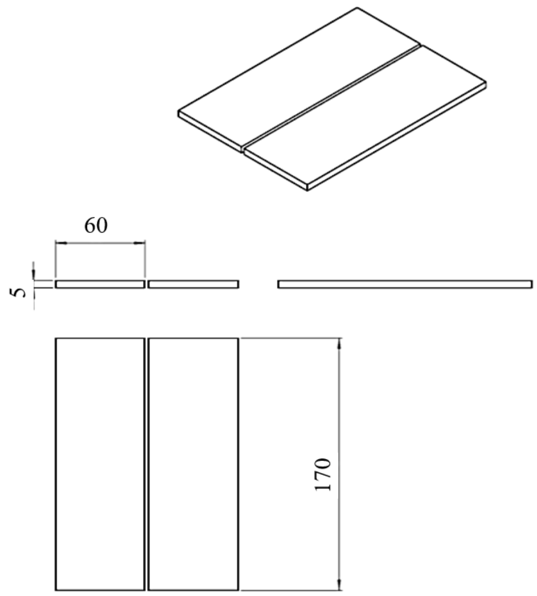


Figure 1 Schematic of the workpiece used in the present work.

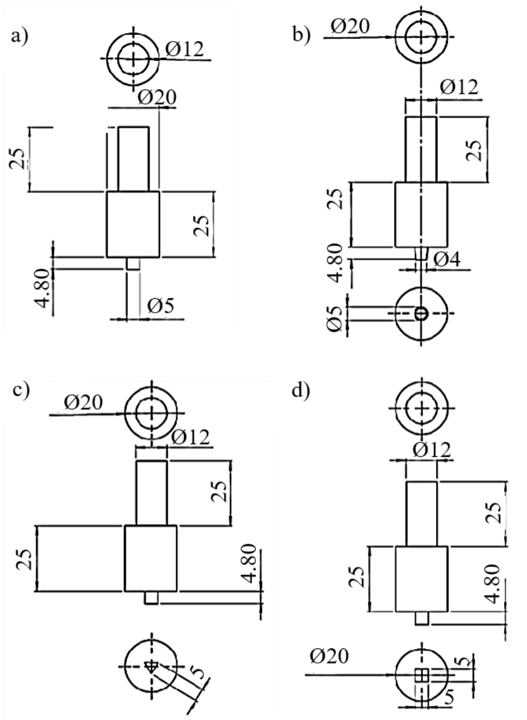


Figure 2 Schematic of the tool pin profiles used in the present work, (a) cylindrical (b) cylindrical (tapered) (c) triangular (d) square.

Table 2 Tool specifications

Tool shoulder	**20 mm (flat surface)**	
Tool pin configuration	**Cylindrical, Cylindrical - Taper, Square and Triangular**	
Pin depth	**4.8 mm**	
Pin Size	Cylindrical	ϕ 5 mm
	Triangle	(Side) 5 mm
	Cylindrical-Taper	D = ϕ 5mm
		d = ϕ 4 mm
	Square	(Side) 5 mm

Table 3 Experimentation details

Parameters	Level 1	Level 2	Level 3	Level 4
Rotational Speed (rpm)	800	1000	1200	1400
Feed (mm/min)	100	120	140	160
Tool Offset (mm)	-0.5	0	0.5	1
Tool Pin Profile	Square (Sq.)	Triangle (Tr.)	Cylindrical (Cyl.)	Cylindrical-Taper (Cyl. Tp.)

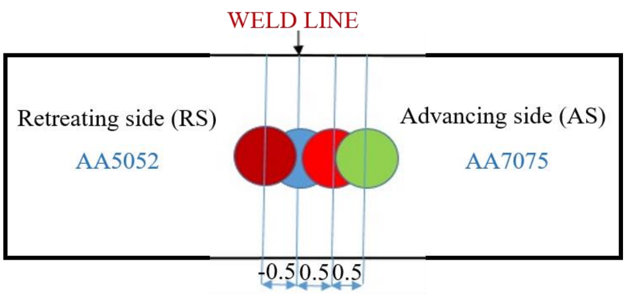


Figure 3 Pictorial representation of the tool offset

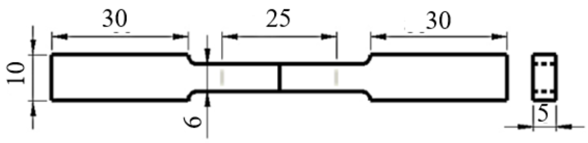


Figure 4 Schematic of the tensile test specimen.

2.3 Experimental methods

AA 7075 and AA 5052 alloys are welded together by friction stir welding process on an ETA make 10T model horizontal FSW machine. The process is carried out as per the Design of Experiments (DOE) table framed in accordance with L16 orthogonal array considering TAGUCHI design model from Minitab Software. The process parameters and their limits are selected in the present work based on the preliminary trials and the subsequent review of the literature and machine capabilities from which the parametric levels are fixed within the minima-maxima band and the tool pin profile is selected based on the review of the existing literature and geometrical considerations from the hand book of FSW process [35]. The process parameters considered in present work involved design specific parameters like tool rotational speed (800, 1000, 1200 and 1400 rpm), transverse feed (80, 100, 120 and 140 mm/min) and tool pin configuration (cylinder, cylinder-taper, triangular and square) and tool offset of (-) 0.5 mm, 0 mm, 0.5 mm and 1 mm; the tool offset refers to the shift in the tool center from the centerline of the weld joint, i.e., tool center is typically placed in the centerline of the joint for similar joints such as that of same alloys, however, the shift of the tool pin position from the center line of the joint is termed as tool offset. The pictorial representation of the tool offset is given in Figure 3.

The details of welding parameters and its levels are given in Table 3. During the process of welding, AA 7075 is located on retreating side while AA 5052 is located on advancing side. The tool shoulder is plunged into the plates fastened on the special fixtures clamped on the table of the machine and the FSW process carried out in accordance with the DOE.

2.3.1 Tensile test

The tensile tests are accomplished in accordance with the ASTM E8 standards on an "Instron make electromechanically operated 3300 series UTM of 100 k N capacity at a crosshead rate of 0.2 mm/min". The schematic draft sketch of the tensile test specimen prepared is given in Figure 4.

2.3.2 Hardness test

The micro-hardness tests are accomplished in accordance with the ASTM E-92 standards on a "Quali-Test make Vickers micro-hardness tester of a 2 kg load capacity", for the weld joint. The unit of hardness given by the test is known as the Vickers Pyramid Number (HV).

3. Results and discussions

Aluminium AA 7075 and Aluminium AA 5052 alloys are welded together by friction stir welding process on an ETA make 10T model horizontal FSW machine. The process is carried out in accordance with the DOE table framed in accordance with L16 orthogonal array considering TAGUCHI Design model from Minitab Software (Table 4). The photographic images of the workpieces before FSW process and after the FSW process is given in Figures 5(a) and 5(b) respectively.

In the present work, experimental trials are carried out and the statistical validations are accomplished based on TAGUCHI methods, which includes experimental trials in accordance with L16 orthogonal array and TAGUCHI analysis to find the S/N ratios, Mean of Means and ANOVA. TAGUCHI method is a scientifically disciplined technique used for evaluating and optimizing the process parameters. The optimizations are aimed at improving the desired characteristics and simultaneously reducing the number of defects by studying the key variables controlling the process and optimizing the procedures or design to yield the best results.

The micro hardness and tensile tests are carried out on one specimen each for the 16 experimental trials, i.e., for a total of 16 specimens for each test and the test results of the 16 experimental trials are tabulated. The works of Raweni et al., have been referred, and the base for DOE is also validated with the findings of the reference article [39]. The Figure 6 gives the photographic images of the tensile test specimens before and after fracture.

Table 4 DOE - L16 Orthogonal array

Exp. No.	Rotational speed (rpm)	Feed (mm/min)	Tool offset (mm)	Tool pin profile	Micro-hardness (HV)	Tensile strength (MPa)
1	800	100	0	Sq.	80.5	192.7
2	800	120	0.5	Tr.	82.7	196.5
3	800	140	-0.5	Cyl.	83.9	201.4
4	800	160	1	Cyl. (Tp.)	87	205.6
5	1000	100	0.5	Cyl.	89.2	212.9
6	1000	120	0	Cyl. (Tp.)	92.5	221.6
7	1000	140	1	Sq.	85.2	203.9
8	1000	160	-0.5	Tr.	83.6	200.7
9	1200	100	-0.5	Cyl. (Tp.)	96.5	227.1
10	1200	120	1	Cyl.	93.8	224.5
11	1200	140	0	Tr.	88.3	207.6
12	1200	160	0.5	Sq.	90.5	214.2
13	1400	100	1	Tr.	90.7	214.9
14	1400	120	-0.5	Sq.	91.4	218.5
15	1400	140	0.5	Cyl. (Tp.)	93.4	223.2
16	1400	160	0	Cyl.	92.3	220.5

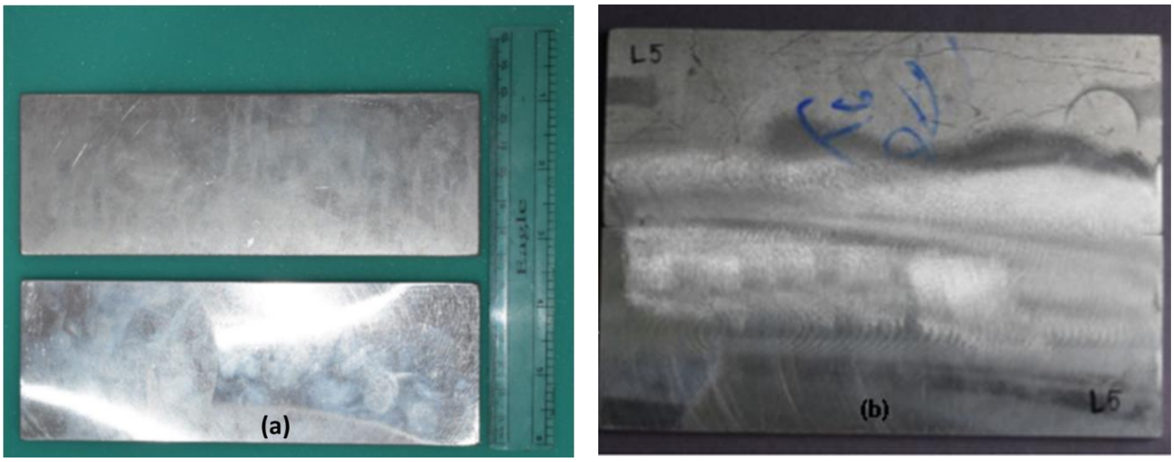


Figure 5 Photographic images of plates (a) before FSW and (b) after FSW

Figure 6 Photographic images of tensile test specimens (a) before fracture and (b) after fracture

Further, the micro hardness and tensile strength values are predicted using regression fitting and the overall error percentage between the outcomes of experimental trials and statistically validated techniques is determined, which turns out to be less than 5%.

Further, the SEM of the fractured surface from the tensile tests are studied to understand the fracture mechanics of the weld joints and evaluate the importance of FSW in improving the fracture resistance characteristics of the weld.

The statistical method of TAGUCHI analysis is considered for the present investigation, and the optimization is achieved by using "Larger-the-Better Signal to Noise ratio". TAGUCHI technique is a process/product optimization method that is based on 8-steps of planning, conduct and evaluation of results of matrix experiments to determine the best levels of control factors. The primary goal is to keep the variance in the output very low, even in the presence of noise inputs. Thus, the process variables are optimized against all variations. In accordance with the steps that are involved in TAGUCHI's method, a series of experiments are to be conducted and statistically validated with the objective function as given in equation (1).

$$S/N = -10 \times \log\left(\left(\Sigma(Y^2)/n\right)\right) \quad (1)$$

Where 'S/N' respresent the sinal to noise ratio 'Y' represents responses for the given factor level combination and 'n' represents in the factor level combination.

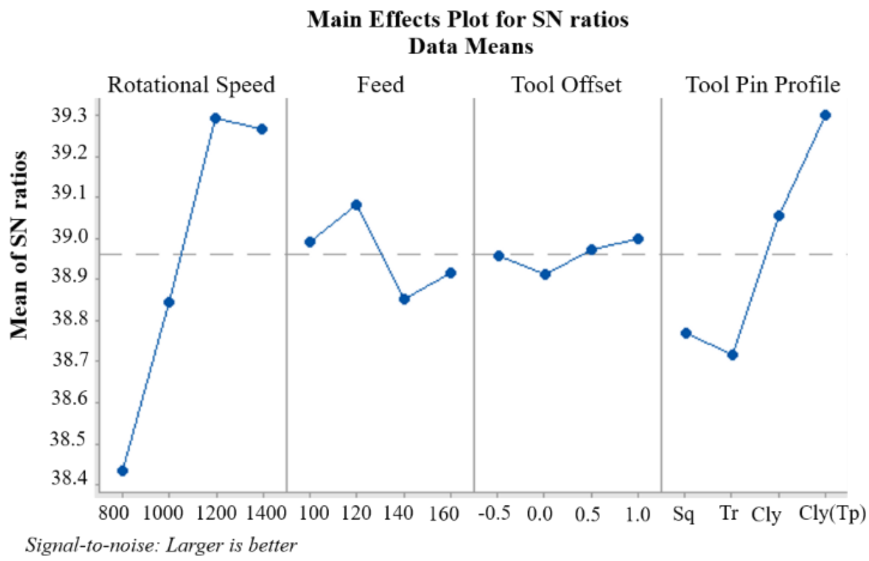


Figure 7 Main effects plot for S/N ratios for micro-hardness

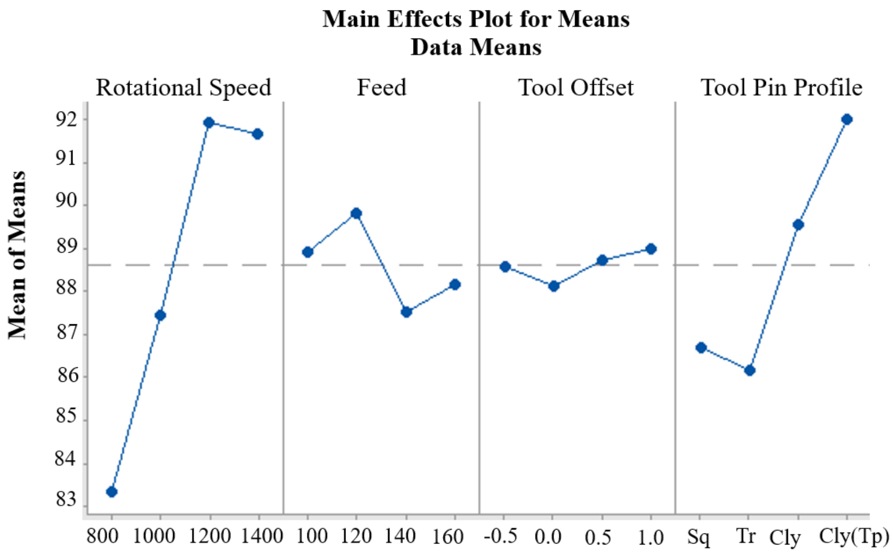


Figure 8 Main effects plot for means for micro-hardness

The significance of the equation is to optimize the set of process parameters to maximize the response, i.e., the micro hardness and the tensile strength.

3.1 TAGUCHI Results for micro hardness

The main effects plot for S/N ratios and means and the response table for S/N ratios and means for micro hardness is given in Figures 7, 8 and Tables 5, 6 respectively. It is herewith seen that the rotational speed is the major factor that needs to be optimized, followed by tool pin profile, feed and tool offset; among these factors, the levels that need to be considered for optimization of the friction stir welding process of the dissimilar aluminium alloy plates for better micro hardness characteristics are: “a rotational speed of 1200 rpm followed by a feed of 120 mm/min, tool offset of 1.0 mm and tool pin profile of cylindrical tapered geometry”.

From the ANOVA Table 7 for micro-hardness, a P-value higher than 0.05 (>0.05) is not statistically significant and indicates strong evidence for the null hypothesis. This means, that the null hypothesis formulated for the statistical validation holds good and the alternative hypothesis are rejected. The null hypothesis framed for each of the parameters are that the parameters selected do not have a significant effect on the micro hardness of the FSW joint, thus from the table, it shall be noted that the feed and tool offset have P-value greater than 0.05, thus contributing minimally to the overall micro hardness of the FSW joint, while the P-value is less than 0.05 for rotational speed and tool pin profile, thereby negating the null hypothesis and validating the fact that these two parameters contribute majorly to the overall micro hardness of the FSW joint.

The model summary in Table 8 clearly indicates that the standard deviation (S) for the micro-hardness among the specimens is 1.40201, while R^2 [R-squared, (R-sq)], tends to be 98.15%, i.e., the R Squared value represents the correlation between the statistical and the experimental outcomes, which denotes that the statistical values are matching by almost 98.15% to the experimental values; the adjusted R^2 [adjusted R-squared, R-sq (adj.)] value tends to be 90.74%, The R^2 should be larger than adjusted R^2, since the adjusted R^2 adjusts the statistic based on the number of independent variables in the model, considering only the significant values.

Table 5 Response table for signal to noise (S/N) ratios (Larger is Better) for micro-hardness

Level	Rotational speed	Feed	Tool offset	Tool pin profile
1	38.43	38.99	38.96	38.77
2	38.85	39.08	38.92	38.72
3	39.30	38.85	38.97	39.06
4	39.27	38.92	39.00	39.30
Delta	0.86	0.23	0.08	0.59
Rank	1	3	4	2

Table 6 Response table for means for micro-hardness

Level	Rotational speed	Feed	Tool offset	Tool pin profile
1	83.53	89.22	88.85	86.90
2	87.63	90.10	88.40	86.33
3	92.28	87.70	88.95	89.80
4	91.95	88.35	89.17	92.35
Delta	8.75	2.40	0.77	6.02
Rank	1	3	4	2

Table 7 ANOVA for micro-hardness

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Rotational Speed	3	204.787	68.2623	34.73	0.008	64.322
Feed	3	13.102	4.3673	2.22	0.264	4.115
Tool Offset	3	1.272	0.4240	0.22	0.880	0.400
Tool Pin Profile	3	93.322	31.1073	15.83	0.024	29.312
Error	3	5.897	1.9656			1.852
Total	15	318.379				100

Table 8 Model summary

S	R-sq	R-sq(adj.)
1.40201	98.15%	90.74%

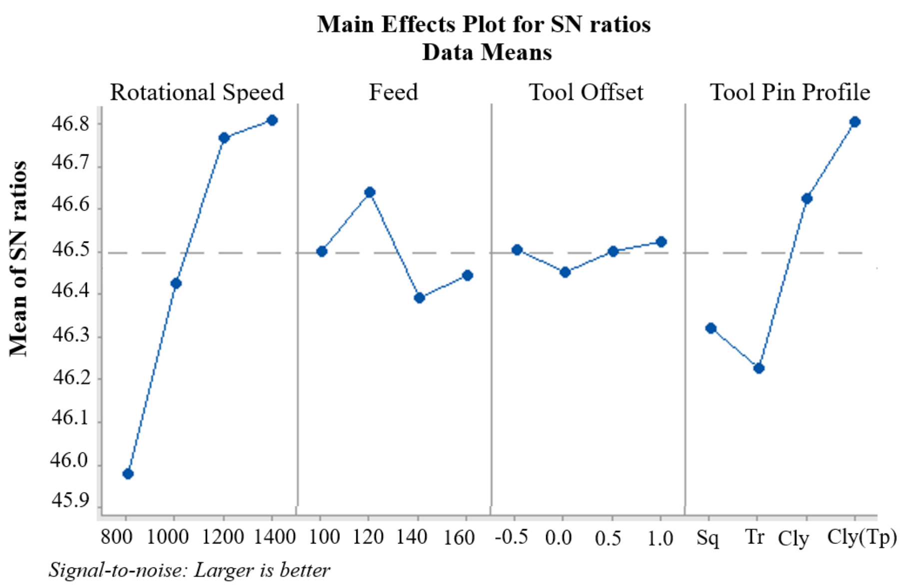


Figure 9 Main effects plot for S/N ratios for tensile strength

3.2 TAGUCHI Results for tensile strength

The main effects plot for S/N ratios and means and the response table for S/N ratios and means for tensile strength is given in Figures 9, 10 and Tables 9, 10 respectively. It is herewith seen that the rotational speed is the major factor that needs to be optimized, followed by tool pin profile, feed and tool offset; among these factors, the levels that need to be considered for optimization of the friction stir welding process of the dissimilar aluminium alloy plates for better tensile strength characteristics are: “a rotational speed of 1400 rpm followed by a feed of 120 mm/min, tool offset of 1.0 mm and tool pin profile of cylindrical tapered geometry”

From, the ANOVA Table 11 for tensile strength, it shall be noted that the feed and tool offset have P-value greater than 0.05, thus contributing minimally to the overall tensile strength of the

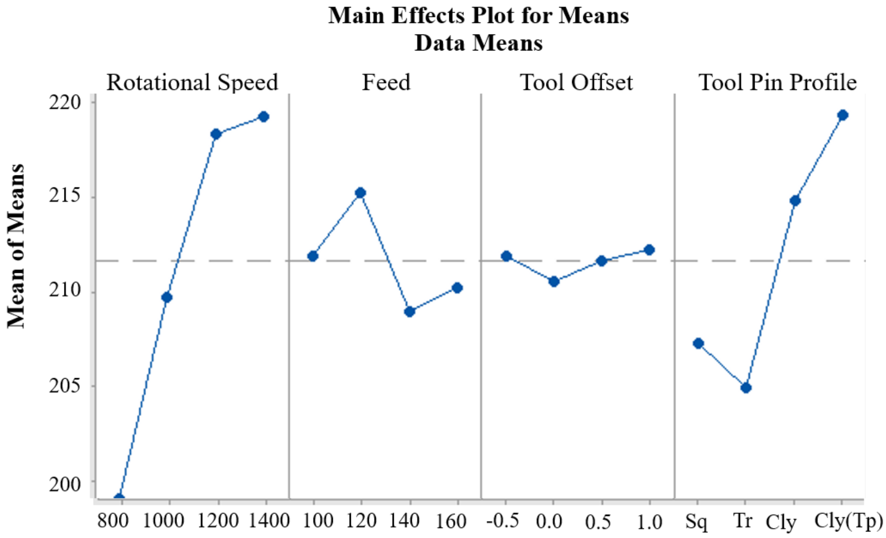


Figure 10 Main effects plot for means for tensile strength

Table 9 Response table for S/N ratios for tensile strength

Level	Rotational speed	Feed	Tool offset	Tool pin profile
1	45.98	46.51	46.51	46.32
2	46.43	46.65	46.46	46.23
3	46.78	46.40	46.51	46.63
4	46.82	46.45	46.53	46.82
Delta	0.84	0.25	0.07	0.59
Rank	1	3	4	2

Table 10 Response table for means for tensile strength

Level	Rotational speed	Feed	Tool offset	Tool pin profile
1	199.1	211.9	211.9	207.3
2	209.8	215.3	210.6	204.9
3	218.4	209.0	211.7	214.8
4	219.3	210.3	212.2	219.4
Delta	20.2	6.3	1.6	14.5
Rank	1	3	4	2

Table 11 ANOVA for tensile strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Rotational Speed	3	1061.20	353.734	63.96	0.003	62.177
Feed	3	88.19	29.398	5.32	0.102	5.167
Tool Offset	3	6.02	2.008	0.36	0.786	0.353
Tool Pin Profile	3	534.73	178.243	32.23	0.009	31.330
Error	3	16.59	5.531			0.972
Total	15	1706.74				100

FSW joint, while the P-value is less than 0.05 for rotational speed and tool pin profile, thereby negating the null hypothesis and validating the fact that these two parameters contribute majorly to the overall tensile strength of the FSW joint.

The model summary in Table 12 clearly indicates that the standard deviation (S) for the tensile strength among the specimens is 2.35177, while R-square (R-Sq) tends to be 99.03%, and the adjusted R-square [R-Sq (adj.)] value tends to be 95.14%, i.e., the statistical values are in close correlation with the experimental trials. The R^2 should be larger than adjusted R^2, since the adjusted R^2 adjusts the statistic based on the number of independent variables in the model, considering only the significant values.

Kowalczyk, et al., [40], have carried out similar set of experiments and accomplished TAGUCHI's validations. The optimum design was determined to be: rotational speed - L2, welding speed - L3 and tilt angle - L3. It should be noted that the above combination of factor levels is among the sixteen combinations tested in the experiment for optimization.

Ardak et al., [41], have carried out work on the formulation of a model and analysis using response surface methods in MINITAB software and their findings are in parlance with the statistical outcomes of the present work.

Salihi et al., [42], have reported the significance of statistical validations in optimization of process parameters for friction stir processing and the findings have sufficed the use of optimization techniques for statistical validations of the experimental trials carried out.

3.3 TAGUCHI Predictions and contour plots

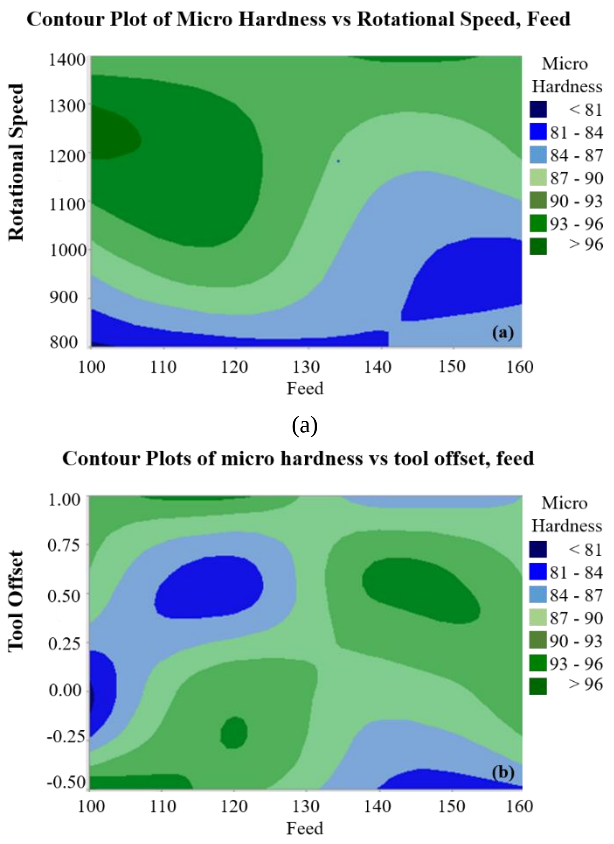
The response tables are examined and main effects plot are used to identify the major factors and the effects of S/N ratio. The standard deviation from the outcomes of the experimental trials

Table 12 Model summary

S	R-sq	R-sq(adj.)
2.35177	99.03%	95.14%

Table 13 Experimental and predicted results

Exp. No.	Micro Hardness (HV)	Predicted values	% Error	Tensile strength (MPa)	Predicted values	% Error
1	80.5	81.52	1.27	192.7	194.04	0.69
2	82.7	82.37	0.40	196.5	196.11	0.20
3	83.9	83.34	0.66	201.4	199.99	0.70
4	87	86.87	0.15	205.6	206.06	0.22
5	89.2	89.07	0.15	212.9	213.36	0.22
6	92.5	91.94	0.60	221.6	220.19	0.64
7	85.2	84.87	0.39	203.9	203.51	0.19
8	83.6	84.62	1.22	200.7	202.04	0.67
9	96.5	96.17	0.34	227.1	226.71	0.17
10	93.8	94.82	1.09	224.5	225.84	0.60
11	88.3	88.17	0.15	207.6	208.06	0.22
12	90.5	89.94	0.61	214.2	212.79	0.66
13	90.7	90.14	0.61	214.9	213.49	0.66
14	91.4	91.27	0.14	218.5	218.96	0.21
15	93.4	94.42	1.09	223.2	224.54	0.60
16	92.3	91.97	0.36	220.5	220.11	0.18



(a)

(b)

Figure 11 Contour plots for (a) micro hardness (HV) vs rotational speed, feed, (b) micro hardness (HV) vs tool offset, feed.

are used to predict the statistical results and validate. Further, from the prediction results, the combination of factors that are closer to the experimental trials are identified for the desired mean without significantly reducing the S/N ratio and the percentage error between the outcomes of the experimental values and predicted values are determined.

The terms that are majorly considered for the TAGUCHI predictions include the tool rotational speed, feed, tool offset and tool pin profile.

From, the TAGUCHI predictions in Table 13, it is herewith validated that the experimental methodology is well established in accordance with the Design of Experiments (DOE) and the optimized set of process parameters have yielded the experimental outcomes which are in close correlation with the statistically predicted results and the errors between them is less than 5%.

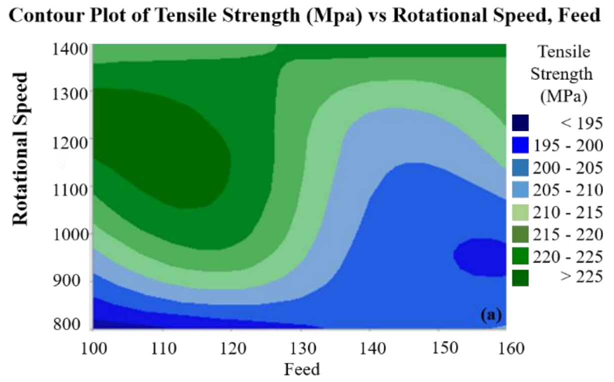
Nourani et al., [43], have carried out work on the multi objective optimization of FSW process parameters on aluminium alloys using TAGUCHI based Grey Relation Analysis. Their research findings report the optimization of process parameters in friction stir welding (FSW) of Aluminum Alloy AA 5083 with multiple responses based on orthogonal array with grey relational analysis. The L9 orthogonal array of TAGUCHI experimental design is used for optimizing the FSW process parameters on tensile strength of FSW welds and total input power required for the process.

Pachal et al., [44] have reported TAGUCHI method with grey relation analysis and have worked on multiple performance characteristics with TAGUCHI's technique for optimizing the process parameters during the optimization of turning operations.

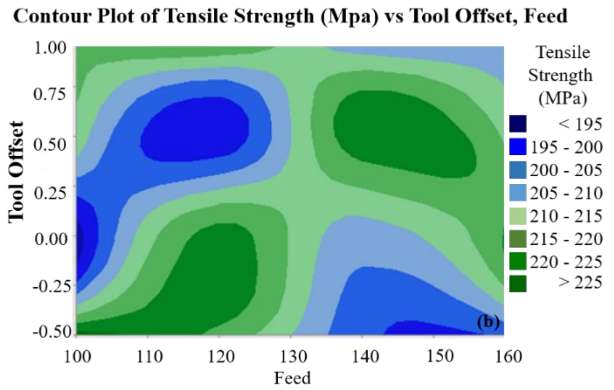
Pawar et al., [45], have worked on unconventional methods to optimize the governing process parameters of friction stir welding towards the mechanical properties and the weld quality. They have reported the effect of contour plots and optimizations on the processing of weld joints and statistical validations of the experimental outcomes.

The contour plots also depict that the tensile strength of the weld joint is highest for the optimized results thus justifying the use of statistical techniques for optimizing the process parameters to obtain better weld joints of dissimilar aluminium plates for aircraft structures.

Further, the Figure 11 gives the contour plots for micro hardness of the friction stir welded specimens, detailed inferences drawn from the TAGUCHI optimizations are validated from the contour plots for micro hardness, wherein the micro hardness is maximum for rotational speed in between 1200 rpm and 1300 rpm and feed in between 100 mm/min and 110 mm/min, while the characteristic property of micro-hardness is



(a)



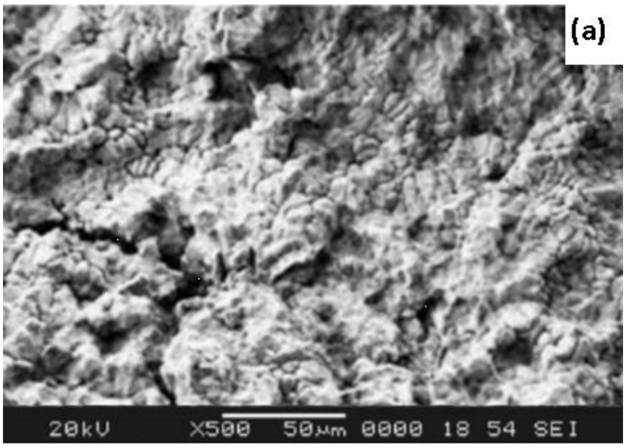
(b)

Figure 12 Contour plots for (a) tensile strength (MPa) vs rotational speed, feed, (b) tensile strength (MPa) vs tool offset, feed.

maximum for tool offset between 0.5 mm and 0.75 mm, and for feed values ranging between 138 mm/min and 155 mm/min.

Similarly, from the contour plots for tensile strength in Figure 12, it is herewith validated that the tensile strength is maximum for rotational speed varying in the range of 1100 rpm to 1300 rpm, and feed varying in between 100 mm/min and 130 mm/min and for tool offset varying in between negative (-) 0.50 mm and 0 mm, 0.25 mm and 0.75 mm respectively. This is also validated from the results of TAGUCHI optimization techniques.

The experimental trials and TAGUCHI predictions for micro hardness (HV) and tensile strength (MPa) have clearly provided the validated design of experiments for process optimization of friction stir welding for weld joint with higher tensile strength and micro hardness. This is also in line with the findings of Ackiel et al., [46], reporting that the optimization of welding parameters eventually leads to better process control and stronger weld joint, this is majorly achieved by TAGUCHI methods and governing parameters. Further, the works on optimization of friction stir welding process carried out by Ramesha K et al., [47], have given sufficient information on validation of experimental trials with statistical values and have reported that the error percentage between the experimental outcomes and the statistical values should lie within 5%, which is relevant to the values in this paper, as the error between the hardness values and tensile strength values determined experimentally and the values determined statistically are within the limits of a nominal of 1%. The review of Ethiraj et al., [48], on submerged friction stir welding has discussed in vast on the influence of the process parameters and the need to optimize them for stronger joints in friction stir welding as well as the submerged counterpart, this key aspect has been validated in the findings of the current paper, thereby reiterating the fact that design and optimization of process parameters is important for better friction stir weld joint.



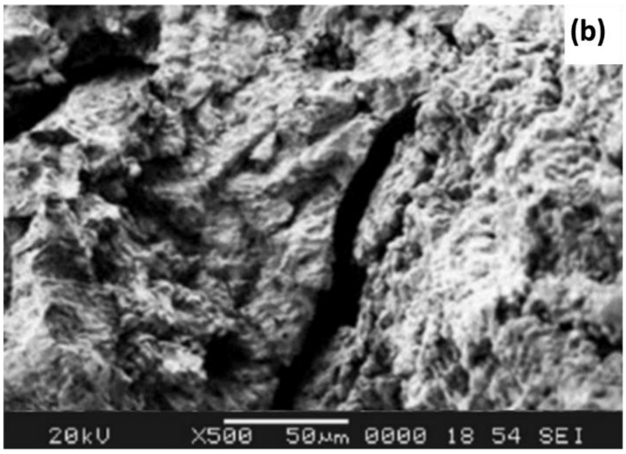


Figure 13 SEM Images of the fractured surface of (a) specimen from L1 experimental trial and (b) specimen from L9 experimental trial.

3.4 SEM of the fractured surfaces

The fracture surface of the FSW joint for L1 and L9 experimental trials are given in the Figures 13 (a) and 13 (b) respectively, i.e., for the specimens of experimental trials exhibiting lowest and highest tensile strengths, the SEM image for fractured specimen from L1 experimental trial has large dimples and heavy shear deformation prior to failure. But in the case of the fractured specimen from L9 experimental trial, it can be seen that the extent of ductile dimpling has decreased with the use of cylindrical (taper) pin profile, friction stir welded at a tool rotational speed of 1200 rpm, feed of 100 mm/min and tool offset of -0.5 mm. The dimple size has been reduced significantly and the nature of failure of the interconnecting ligaments is by ductile tearing.

The fractured specimen surface revealed a number of fractured particles. The particle fracture was often associated with the more elongated particles, which were aligned with the tensile direction. Fracture studies conducted on the tensile fracture surface of the friction stir welded specimens revealed a typical quasi-brittle fracture exhibiting interfacial deboning.

The results of the fracture surface analysis indicate an increase in brittleness from the L1 to L9 experimental trial. The presence of uniformly distributed dimples observed on the fractured surface of the unreinforced samples indicates a relatively ductile failure

Fracture studies carried out thus gives an overview of the micro-porosities and its effect on the fracture of the composite specimens subjected to loading and subsequent deformation leading to the initiation of cracks that propagates and ultimately causes the failure of the materials. The luder bands formed results in interstitial residual stresses that will eventually yield and fracture the material {XE “material”}

Dipti Kanta Das et al., [49], has effectively carried out research on the fracture characteristics of aluminium specimens and have found that the rupture strength increases with the friction stir processing of the weld joints, that eventually leads to resistance to the fracture of the specimens and its subsequent propagation.

4. Conclusions

The critical analysis of the outcomes of the experimental design and optimization of the process parameters for friction stir welding has yielded several conclusions which are comprehensively put forth in the current section.

From, the statistical validations of the results for tensile strength and micro hardness, it has been found out that the friction stir welding, if conducted at an optimized set of process parameters of 1200 rpm tool rotational speed, 120 mm/min feed rate, tool offset of 1.0 mm and using tool of cylindrical taper pin profile, an effective weld of AA 7075 and AA 5052 alloy shall be produced. Further, it has been observed that welds produced at higher tool rotational speed and moderate feed rate gives higher output values, when a cylindrical taper pin profile is used, i.e., the weld joints obtained have higher tensile strength and micro hardness with the optimization of process parameters. Hence, FSW process can be employed for joining plates and obtaining weld joints with higher tensile strength and micro hardness.

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