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Optimization of Process Parameters for Friction Stir Welding of Aluminium Alloy by Taguchi Method

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Friction stir welding, a solid state joining technique, is widely being used for joining Aluminium alloys for aerospace, marine, automotive and many other applications of commercial importance. FSW trials were carried out using a vertical milling machine on AA1050-A alloy. The tool geometry was carefully chosen and fabricated to have a nearly flat welded interface. Important process parameters that control the quality of the weld are (a) rotation speed (rpm) (b) traverse speed (mm/min) (c) tool tilt angle (degree) (d) tool tip design. We did analysis by putting various values of these different are meters and conclude the best result to optimize the process parameters by using Taguchi method. It is observed that, the rotational speed has 62.57% contribution, welding speed has 6.06% contribution, tilt angle has 20.88% contribution and tool tip design has 10.59% contribution to Tensile strength of welded joints.
Keywords: Friction stir welding, AA1050-A alloy, microstructure, mechanical properties, Taguchi Method, ANOVA.

1. Introduction

Friction Stir Welding was invented by Wayne Thomas at TWI (The Welding Institute) Cambridge, and the first patent applications were filed in the UK in December 1991[1]. FSW is a solid-state process, which means that the objects are joined without reaching melting point. Using FSW rapid and high quality welds of 2xxx and 7xxx series alloys, traditionally considered unweldable, are now possible. In FSW, a cylindrical shouldered tool with a profiled pin is rotated and plunged into the joint area between two pieces of sheet or plate material. The parts have to be clamped to prevent the joint faces from being forced apart. Frictional heat between the wear resistant welding tool and the work pieces causes the latter to soften without reaching melting point, allowing the tool to traverse along the weld line. The plasticized material, transferred to the trailing edge of the tool pin, is forged through intimate contact with the tool shoulder and pin profile. On cooling, a solid phase bond is created between the work pieces. Material thicknesses ranging from 0.5 to 65 mm can be welded from one side at full penetration, without porosity or internal voids. In terms of materials, the focus has traditionally been on non-ferrous alloys, but recent advances have challenged this assumption, enabling FSW to be applied to a broad range of materials.

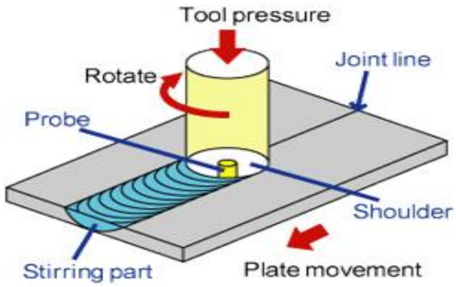


Fig.1. Friction stir welding

Friction stir welding technique had many advantages such as high quality, low cost, low energy consumption, and environment friendly and there is no necessity for gas shielding for welding aluminium. Mechanical properties as proven by fatigue, tensile tests are excellent. There is no fume, no porosity, no spatter and low shrinkage of the metal. In particular, FSW is currently under extensive investigation for joining aluminium alloys in the aerospace industry.[2] Friction stir welding was considered to be the most significant development for metal joining in the past two decades.[3] Although it was a solid state welding method, the FSW could still suffer from significant levels of residual stress, and associated distortion, which could be similar in magnitude to that found in fusion welds.[4] During fabrication, distortion can be a significant problem, and expensive post-weld repair procedures are sometimes necessary to overcome it.[5] In order to reduce these defects, a liquid CO_2 cooling technique was applied during FSW process.[6] The cooling introduced a thermal tensioning effect on the cooling weld metal counteracting the forces which led to residual stresses and distortion.[7] However, with regard to local cooling, the cooling substances might contaminate the weld metal.[8] Thermal stress engineering techniques, global preheating and local thermal tensioning, were proposed.[10]

Global preheating of the components reduced the temperature gradient between the weld material and the surrounding parent metal. The amount of plastic strain generated during welding will decrease, resulting in the reduction of residual stresses.[9] The local thermal tensioning introduced a local tensile strain which led to plastic elongation of the weld line material and the plastic elongation resulted in the reduction of residual stress.[10] However, it was not easy to weld the large plate with the thermal tensioning.[8] In recent years, a new technique about application of rolling pressure had been invented.[9] By using two rollers placed either side of the weld line following the FSW tool introduced significant compressive stresses in the roller contact area.[9] One roller placed along the weld directly trailing the FSW tool could also help reduce the tensile weld line stresses significantly.[9] Moreover, a surface enhancement technology which was called low plasticity burnishing (LPB) was used to reduce the tensile residual stress and distortion. Low plasticity burnishing tooling which was comprised of a ball that was supported in a spherical hydrostatic bearing was designed to process the weld surface after the FSW operation, producing a FSW seam with superior fatigue strength and surface finish.[11] This technology had been demonstrated to produce a deep layer of highly compressive residual stress.[12] In the present work, a new technique of in situ rolling friction stir welding (IRFSW) was developed to reduce the residual stress and distortion, eliminate the weld flashes and improve the corrosion resistance of FSW seams.

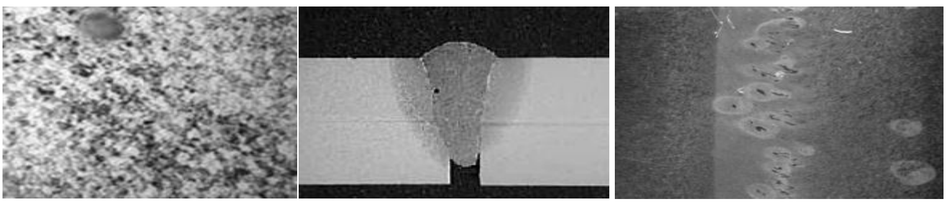
2. Experimental Work

From reported [13] primary and secondary process parameters, three primary process parameters [tool rotational speeds (N), transverse speeds (S), tilt angle (Ø) and tool tip design (D)] are selected for the study. These parameters contribute to heat input and influence tensile strength of friction stir weld for aluminium alloy joints. A large number of trial were conducted on flat of 6 mm thickness and 35 mm wide AA1050 aluminium alloy to find out feasible working limit of FSW process parameters. Chemical composition of AA 1050 alloy is given in (table 1).

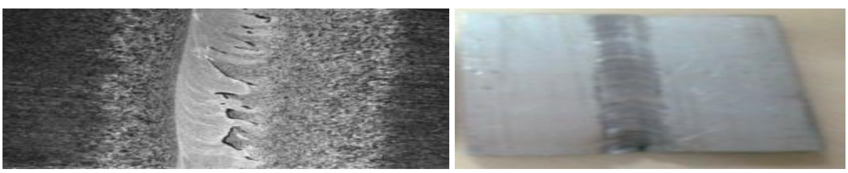
Table 1 Chemical composition of work material AA 1050-A

Elements	Cu	Mg	Si	Fe	Mn	Zn	Ti	Al
Percentage	0.05	0.05	0.25	0.4	0.05	0.07	0.05	Balance

Working range of each parameter was decided by inspecting macrostructure. From the inspection following observation are made: (a) when tool rotation speed was lower than 600 rpm, tunnel defect was observed (fig. 2a) which is due to insufficient heat generation and insufficient metal transportation. When tool rotation speed is higher than 1300 rpm, piping defect was observed (fig. 2b) which is due to excess turbulence caused by high tool rotation speed. (b) When tool transverse speed was lower than 11mm/min, tunnel defect was observed (fig. 2c) which is due to excess heat input per unit length. When tool transverse speed is higher than 28mm/min, tunnel defect was observed (fig. 2d) which is due to inadequate flow of material caused by insufficient heat input. (c) When tool tilt angle is greater than 2 degree rough surface is observed (fig. 2e) in welding.



(a) 600 rpm (b) 1300 rpm (c) 11 mm/min



(d) 28 mm/min (e) 3 degree

Fig.2 macrostructure of FSW joints

In this experiment we applied Taguchi method for optimization of process parameters, as per array selector if we are having three parameters and each parameter have three level (table. 2) then we have to conduct nine experiment. The orthogonal table in Taguchi designed by Ross states that for nine experiments and three parameter we have to prepare three specimens for each experiment.

Table 2: Welding Parameters and Tool Dimensions

Process parameters and tool details	Values
Rotational speed (N in rpm)	700,900,1100
Transverse speed (S in mm/min)	14,18,23
Tool tilt angle (Ø in degree)	0,1,2
Tool tip design	Cylindrical, tapered, square
Tool shoulder diameter (D)	10.0 mm
Pin diameter (d)	3.0 mm
Shoulder penetration in work surface	3.5 mm

The flat of 6 mm thickness and 35 mm wide AA1050-A aluminium alloy were cut into size 60 mm and these pieces are filed properly to have fine surface. The friction stir welding was obtained by securing the plates in butt position with the help of fabricated fixture of a milling machine. The direction of welding was normal to the rolling direction. Welding was carried out in a single pass using non-consumable tools made of HSS M2 having hardness 61 to 63 HRC, tool is having conical pin and flat shoulder. The tensile specimens were prepared as per ASTM E8M-04 (fig. 3). Three specimens were prepared for each experiment as per configuration of parameter.

Fig. 3 Dimension of flat tensile specimen

Tensile test was carried out in 100kN, servo controlled Universal Testing Machine (Make: A.S.I Sales Private Limited, ISO 9001:2000 CO.) Three results and their average and S/N ratio are given in table 3.

Table 3 Experimental values of tensile strength (Mean) and S/N ratio

Exp.	Input parameter				Response (Z_i)			Mean Value	S/N ratio
	N	S	Ø	D	Trail 1	Trail 2	Trail 3		
1	700	14	0	C	96.67	94.21	89.47	93.45	39.40
2	700	18	1	T	88.10	87.14	90.81	88.68	38.95
3	700	23	2	S	85.71	90.00	91.81	89.17	38.99

4	900	14	1	S	85.24	87.81	89.43	87.49	38.83
5	900	18	2	C	97.14	90.48	99.14	95.59	39.59
6	900	23	0	T	100.71	97.14	97.33	98.39	39.86
7	1100	14	2	T	97.14	100.00	97.57	98.24	39.84
8	1100	18	0	S	99.95	101.48	101.71	101.05	40.09
9	1100	23	1	C	99.05	101.90	99.90	100.28	40.02

3. Results and Discussion

In order to assess influence of factors on response means and signal to noise ratio (S/N) for each control factor are to be calculated. Signals are indicators of effect on average response and noises are measures of deviation from experimental output. In this study S/N ratio is considered for criteria larger the better for maximum response. It is given by expression as follows, where n is total no of trial, Z_i is tensile strength of specimen in MPa.

S/N ratio = $-10 \text{ Log } \{1/n \, \Sigma \, (1/z_i^2)\}$

Analyzing mean and S/N Ratio of various process parameters (table 4); it is observed that a larger S/N Ratio corresponds to better quality. Therefore, optimum level of process parameter is the level of highest S/N Ratio. S/N Ratio (fig. 4) and Mean effect (fig. 5) for tensile strength calculated by software indicates that strength is maximum when N is 1100 rpm. (Level 3), S is 18 mm/min (level 2), Ø is 0 degree (level 1) and D is cylindrical (level 1)

Table 4.Main effect of tensile strength (means and S/N ratios)

Source	Mean				S/N Ratio			
	Level-1	Level-2	Level-3	Delta	Level-1	Level-2	Level-3	Delta
N	90.43	93.82	99.86	9.43	39.11	39.43	39.98	0.87
S	93.06	95.11	95.95	2.89	39.36	39.54	39.62	0.26
Ø	97.63	92.15	94.33	5.48	39.78	39.27	39.47	0.51
D	96.44	95.10	92.57	3.87	39.67	39.55	39.30	0.37

Table. 5 ANOVA for tensile strength (means and S/N ratios)

Source	DOF	SS		V		SS^*		P%	
		S/N Ratio	Mean	S/N Ratio	Mean	S/N Ratio	Mean	S/N Ratio	Mean
N	2	1.16	136.89	0.58	68.45	1.16	136.89	61.38	62.57
S	2	0.11	13.26	0.06	6.63	0.11	13.26	5.82	6.06
Ø	2	0.40	45.67	0.20	22.84	0.40	45.67	21.26	20.88
D	2	0.21	23.17	0.11	11.59	0.21	23.17	11.11	10.59
Error	0	0.01	0.22			0.01	0.22	00.53	0.10
Total	8	1.89	218.77			1.89	218.77	100	100

DOF= Degree of freedom, SS= Sum of square, V= Variance, SS*=Pure sum of square, P% = Percentage contribution

With the help of analysis of variance (ANOVA), Percentage contribution of various process parameters in terms of S/N Ratio and mean are given in table. 5. Graphical representation of mean percentage contribution of various parameters is shown in fig. 6.

Formula used for calculation:

1. $SS = n_1(x_1-X)^2 + n_2(x_2-X)^2 + n_3(x_3-X)^2$ Where $X = (x_1 + x_2 + x_3) / 3$ and x_1,x_2,x_3 are mean of parameter as per level.

2. Variance = SS / DOF and DOF = (n-1)

3. Total SS (mean) = $\sum^{9}_{n=1}(\text{mean})^2 - T^2/n$ where T is total value of individual item in sample and n is trial number.

4. $SS^* = SS - (SS_{(Error)} / DOF_{(Error)}) \times DOF_{(Participant)}$

5. P % = (SS^* of individual / SS^* of total)

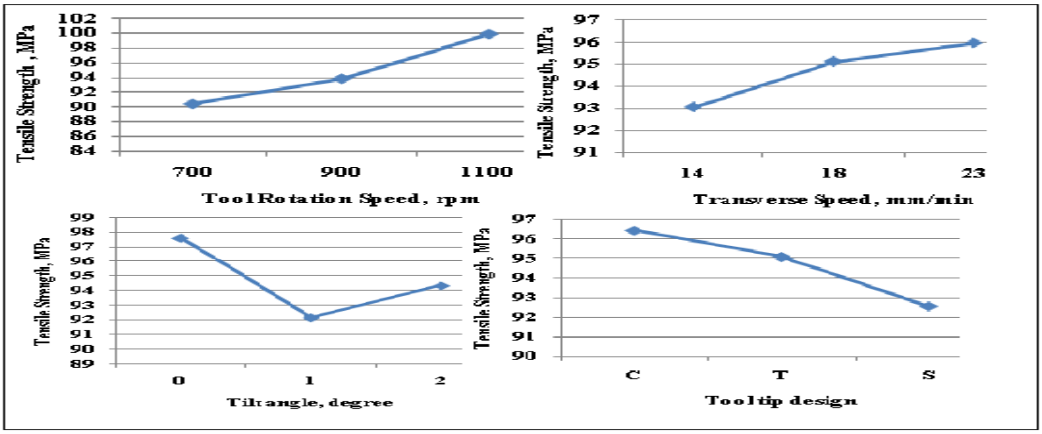


Fig 5.Response graph (mean) of tensile strength

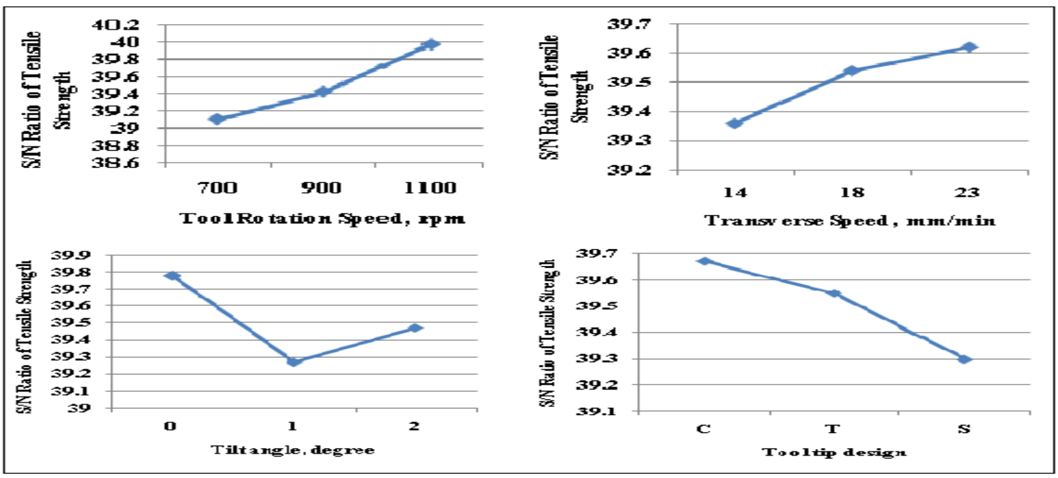


Fig 4. Response graph (S/N ratio) of tensile strength

4. Conclusion

As per experiment conducted on Aluminium alloy AA1050-A rotational speed was the most dominant process parameters for weld strength followed by the welding speed. Percentage of contribution of FSW process parameters was evaluated and found that the rotational speed has 61% contribution, welding speed has 6% contribution, tilt angle has 21% contribution and tool tip design has 11% contribution to Tensile strength of welded joints. The optimum process parameters for the weld strength are the rotational speed of 1100 rpm, the welding speed of 18 mm/min, tilt angle of 0° and tool tip design is cylindrical, indicating that the tensile strength was at maximum when rotational speed is at level 3; welding speed at level 2, tilt angle and tool tip design is at level 1.

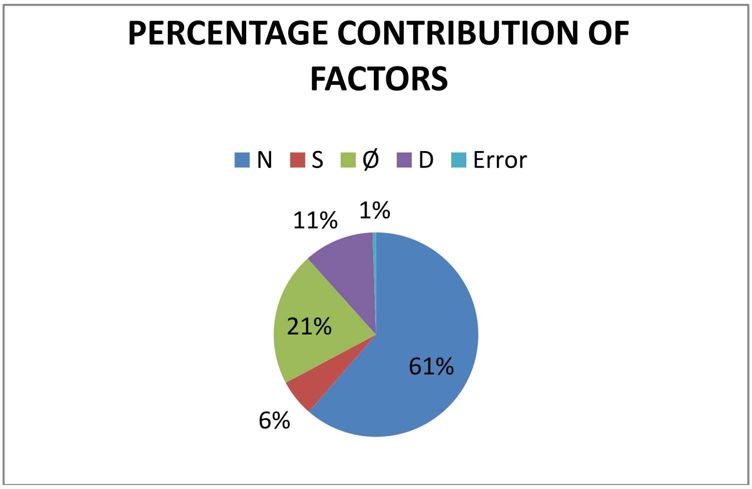


Fig 6. Percentage contribution of factors (mean) and their interactions

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