INTERNATIONAL JOURNAL OF R&D IN ENGINEERING SCIENCE AND MANAGEMENT

Optimization of process parameters for friction stir welding of aluminium alloy AA6101-T6 by Taguchi method

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ABSTRACT

Friction stir welding is a technique of joining similar or dissimilar metal in a solid state; normally it is used for joining Aluminium alloys for spacecraft, submarine, automobile and many commercial importances. FSW was conducted with the help of a vertical milling machine on AA 6101-T6 alloy. The tool geometry chosen comprises of tapered tip with flat shoulder so that flat welded interface can be fabricated. Process parameters that control the quality of the weld are (a) rotation speed (rpm) (b) traverse speed (mm/min) and (c) tool tilt angle (degree). We did analysis by putting various values of these different parameters and conclude the best result to optimize the process parameters by using Taguchi method. It is observed that, the rotational speed has 44.40% contribution, welding speed has 19.10% contribution, and tilt angle has 26.50% contribution to Tensile strength of welded joints.

Key Words: Friction stir welding, AA6101-T6 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. FSW process can weld 2xxx and 7xxx series alloys with high quality, traditional welding of these alloys, are not possible. In FSW, a tool with a profiled tapered pin and flat shoulder is rotated and plunged into the joint area between two metal pieces. These metal parts have to be clamped to prevent the joint faces from being forced apart. Frictional heat developed between the welding tool and the metal work pieces causes the metal contact surface to soften without reaching melting point, allowing the tool to traverse along the weld line. The plasticized material, transferred to the rotating edge of the tool pin, is welded with the help of tool shoulder and pin profile. On cooling, a solid phase bond is created between the metal pieces. Metal thicknesses ranging from 0.5 to 65 mm can be welded from one side at full penetration, without defects. FSW is initially focused on non-ferrous alloys, but now it is applied to a broad range of materials.

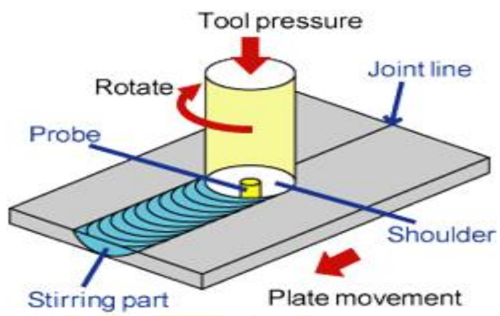


Fig.1. Friction stir welding

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. FSW technology is under research for joining aluminium alloys in the aerospace industry [2]. Friction stir welding is the most significant development for metal joining in the past 20 years [3]. Although FSW is a new technology but it still suffers from residual stress and associated distortion, these defects are similar to that found in fusion welds [4]. During fabrication, distortion is a major problem and to reduce this defects, a liquid CO_2 cooling technique was applied during FSW process [5,6]. The cooling introduced a thermal tensioning effect on the cooling weld metal counteracting the forces which led to residual stresses and distortion [7]. The major demerit of cooling is that cooling substances might contaminate the weld metal [8]. Thermal stress engineering techniques, global preheating and local thermal tensioning, were proposed [10].

Overall preheating of the components reduced the temperature gradient between the weld material and the surrounding parent metal. Due to preheating plastic strain generated during welding will decrease, which result 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. 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.

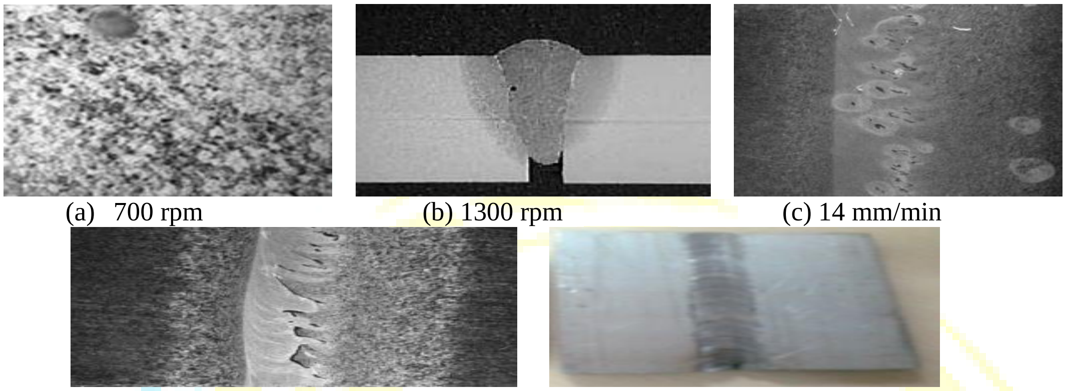
2. EXPERIMENTAL WORK

From reported [13] primary and secondary process parameters, three primary process parameters [tool rotational speeds (N), transverse speeds (S) and tilt angle (Ø)] 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 AA6101 aluminium alloy to find out feasible working limit of FSW process parameters. Chemical composition of AA 6101 alloy is given in (table 1).

Table 1 Chemical composition of work material AA 6101-T6

Elements	Mn	Si	Zi	Cu	Cr	Al
Percentage	0.600	0.500	0.021	0.074	0.015	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 800 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 1250 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 16mm/min, tunnel defect was observed (fig. 2c) which is due to excess heat input per unit length. When tool transverse speed is higher than 25mm/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) 700 rpm (b) 1300 rpm (c) 14 mm/min

(d) 30 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 parameters 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)	800,1000,1250
Transverse speed (S in mm/min)	16,20,25
Tool tilt angle (Ø in degree)	0,1,2
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 AA6101 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.

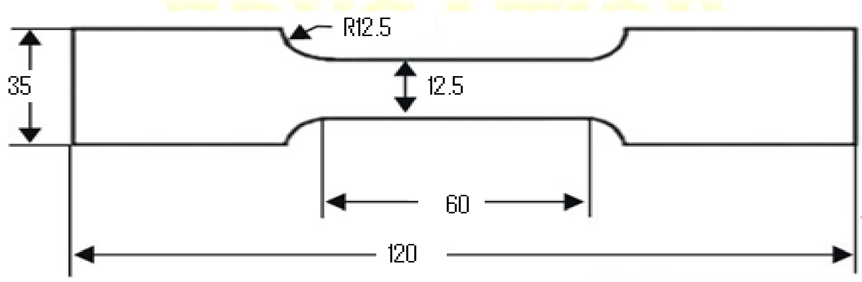


Fig. 3 Dimensions of flat tensile specimen

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	φ	Trail 1	Trail 2	Trail 3		
1	800	16	0	146.67	154.29	149.52	150.16	43.53
2	800	20	1	198.10	197.14	183.81	193.02	45.70
3	800	25	2	165.71	160.00	143.81	156.51	43.84
4	1000	16	1	215.24	203.81	211.43	210.16	46.44
5	1000	20	2	197.14	210.48	197.14	201.59	46.08
6	1000	25	0	165.71	207.14	213.33	195.40	45.65
7	1250	16	2	177.14	160.00	168.57	168.57	44.51
8	1250	20	0	220.95	210.48	225.71	219.05	46.80
9	1250	25	1	199.05	221.90	241.90	220.95	46.80

3. Results and Discussion

In order to predict the influence of individual factor (process parameter), the response means and signal to noise ratio (S/N) 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.

$$\textbf{S/N ratio} = -10 \log \{1/n \ \Sigma\ (1/z_i^2)\}$$

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 1250 rpm. (Level 3), S is 20 mm/min (level 2) and Ø is 1 degree (level 2).

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	166.56	202.38	202.86	35.82	44.36	46.06	46.04	1.70
S	176.30	204.55	190.95	28.25	44.83	46.19	45.43	1.36
Ø	188.20	208.04	175.56	19.84	45.33	46.31	44.81	0.98

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	5.71	2600.99	2.86	1300.49	5.42	2462.34	44.14	44.40
S	2	2.79	1197.65	1.39	598.83	2.50	1059.00	20.36	19.10
Ø	2	3.48	1608.35	1.74	804.18	3.19	1469.70	25.98	26.50
Error	2	0.29	138.65			1.17	554.60	9.53	10.00
TOTAL	8	12.28	5545.64					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) = $\sum_{n=1}^{9}(\text{mean})^2 - T^2/n$ 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)**

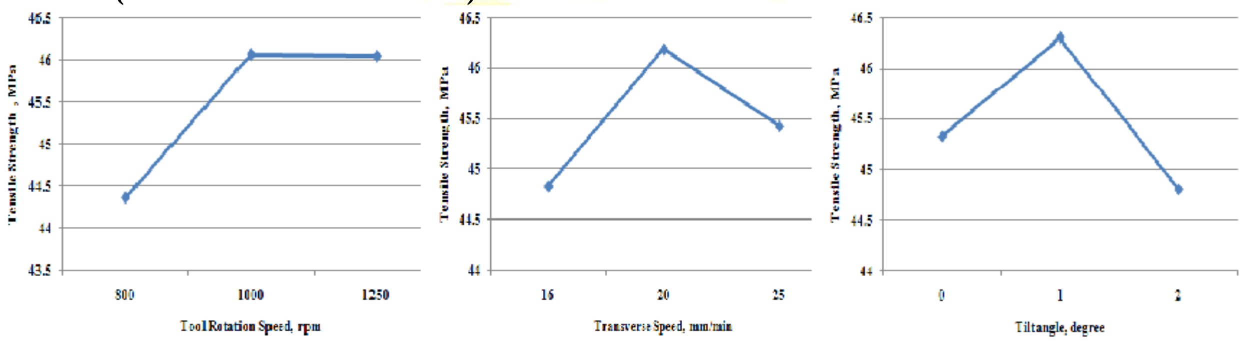


Fig 4.Response graph (S/N ratio) of tensile strength

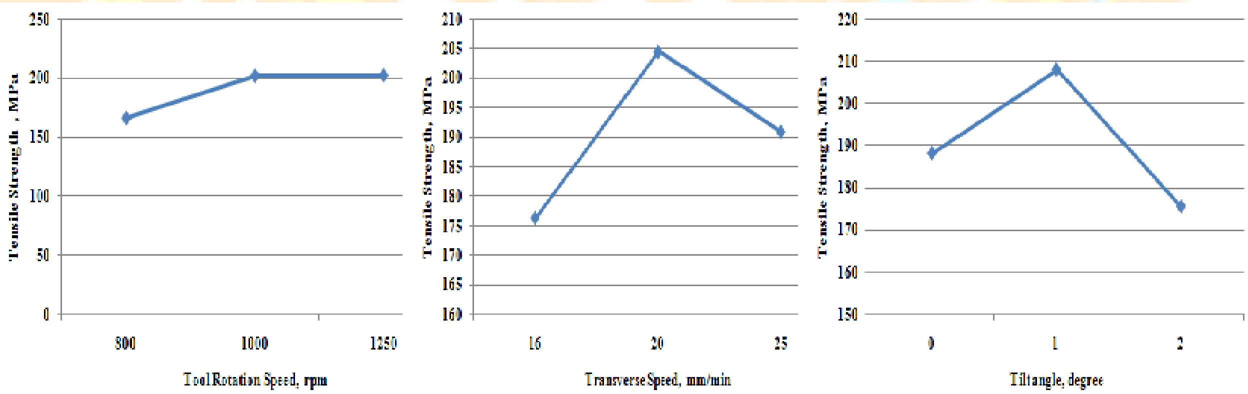


Fig 5.Response graph (mean) of tensile strength

4. CONCLUSION

As per experiment conducted on Aluminium alloy AA6101 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 44.40% contribution, welding speed has 19.10% contribution, and tilt angle has 26.50% contribution to Tensile strength of welded joints. The optimum process parameters for the weld strength are the rotational speed of 1250 rpm, the welding speed of 20 mm/min, and tilt angle of 1°, indicating that the tensile strength was at maximum when rotational speed is at level 3; welding speed and tilt angle are at level 2.

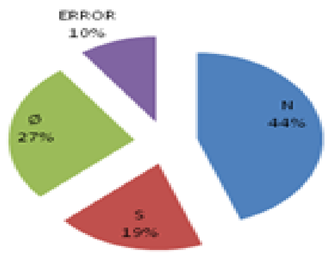


Fig 6. Percentage contribution of factors (mean) and their interactions

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