ISSN 1392–1320 *MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 23, No. 1. 2017*

Property Evaluation of Friction Stir Welded Dissimilar Metals: AA6101-T6 and AA1350 Aluminium Alloys

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crossref http://dx.doi.org/10.5755/j01.ms.23.1.14132

Received 26 February 2016; accepted 15 May 2016

Next to copper, aluminium alloys are widely used in electrical industries, because of their high electrical conductivity. AA6101-T6 and AA1350 aluminium alloys are widely used in electrical bus bars. As these alloys are joined by mechanical fasteners in electrical bus bars, the conductive area has been reduced. To avoid this problem, they should be joined without removal of metal as well as their properties. Friction stir welding technique is mainly invented for joining similar and dissimilar aluminium alloys. In this investigation, friction stir welding was done for AA6101-T6 and AA1350 aluminium alloys by varying tool traversing speed, rotational speed and tilt angle with hexagonal pin profiled tool. The analysis of variance was employed to study the effect of above parameters on mechanical properties of welded joints. From the experimental results, it is observed that welded joint with the combination of 1070 rpm rotating speed, 78 mm/min traversing speed and 2° tilt angle provides better mechanical properties. Analysis of variance shows that most significant impact on tensile strength and micro hardness are made by variation in tool rotating speed while tool tilt angle makes the most significant impact on bending strength.

Keywords: AA6101-T6, AA1350, rotating speed, traversing speed, tilt angle.

1. INTRODUCTION

Compared to conventional fusion welding methods, friction stir welding process has lot of merits such as low distortion, satisfactory dimensional stability and better mechanical properties [1, 2]. The fusion welding of aluminium alloys results in voids, hot cracking and brittle structures in weld zone, which affects the welding properties. Since the conventional fusion welding techniques are not suitable for joining of aluminium alloys, Friction Stir Welding (FSW) technique is applied for welding of aluminium alloys [3, 4]. A good understanding of FSW technique results in better welding properties. Hence, in-depth investigations are needed. Because of their light weight structure, high strength to weight ratio and high conductivity, aluminium alloys are widely used in the aerospace, automobile and electrical industries. Low strength AA1350 and high strength AA6101-T6 aluminium alloys are widely used in electrical industries due to their high electrical conductivity. Hence, welding of these two alloys has wide range of applications in electrical industries

During welding process, a non-consumable rotating tool, which has a cylindrical shoulder, and a pin is inserted into the joint between two plates, which are butted together. The tool shoulder is made to contact the plate surface with a certain load and the tool is moved along the weld line between two plates. The rotation and the forward movement of the wear resistant welding tool generate frictional heat between tool and work piece, which makes the material softened and plastically deformed. Due to the rotational and forward movement of tool, deformed material flows from one side to another side and perfect stirring at weld region is produced. Since the FSW process is conducted below the melting point of the material, it is also called solid state welding process [5, 6]. In this welding technique, joining efficiency highly depends upon the process parameters such as tool rotating speed, traversing speed, tilt angle, axial force and tool geometry [7].

Ghosh et al. [8] investigated the effect of rotation and traversing speed of tool on AA6061-T6 and A356 alloys. High strength AA6061-T6 was placed in advancing side and low strength A356 was placed in retreating side and welding was performed by varying rotation and traversing speed of tool. They found that lower tool rotation and traversing speed yields fine grains in weld nugget, which substantially improves the tensile strength of joint. Ramanjaneyulu Kadaganchi et al. [9] employed response surface methodology to predict the responses of friction stir welds of AA 2014-T6 alloy and found that increment in tool tilt angle results in improvement in the consolidation of material under the shoulder. In addition to that, variation in tool tilt angle also contributes to the formation of surface defects and filling of materials in the weld region [10]. Guo et al. [11] worked on friction stir welding of AA6061 and AA7075 and observed that the mixing of material is very much effective when AA6061 alloy was placed on the advancing side. And all the joints, during tensile tests, got failed at side where the minimum hardness is located in Heat Affected Zone (HAZ). Palanivel et al. [12] joined AA5083-H111 and AA6351-T6 alloys and reported that straight pin profiles cause no defects while tapered profiles cause a tunnel defect at the bottom of joints. Metha et al. [13] analyzed the influence of polygon pins on AA2014-T6 plates. They observed that tools with more number of pin sides such as hexagon pins experience lower shear stress over lesser number of pin sides such as triangular pins during welding. Ashok kumar

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and Thansekhar [14] reported that hexagonal pin profiled tool provides higher tensile properties when compared to triangular and square pin profiled tools. They also found that 15 mm shoulder diameter and 5 mm pin diameter exhibit better mechanical properties.

While joining AA6101-T6 plates, better mechanical properties may be obtained when rotating and traversing speed are in the range of 765 rpm to 1070 rpm and 78 mm/min to 120 mm/min respectively [15]. For welding AA1350 and pure copper, sound welds have been achieved at a rotating speed of 1000 rpm and a traversing speed of 80 mm/min. [16].

To the best of our knowledge, however, the processing window for joining of AA6101-T6 and AA1350 alloys has not been examined. In this present work, the influences of tool rotation speed, traversing speed and tilt angle in dissimilar FSW of AA6101-T6 and AA1350 alloys are assessed and tensile strength, micro hardness, bending strength and microstructures in the weld nugget formed are evaluated. To estimate the relative influences of welding parameters on welded joints, Taguchi L_9 orthogonal array, signal to noise ratio and analysis of variance methods are used.

2. EXPERIMENTAL PROCEDURE

AA6101-T6 and AA1350 aluminium alloys having dimensions of 150 mm × 50 mm × 6 mm were used as the base metals in this present investigation. The chemical compositions and mechanical properties of these Al alloys are shown in Table 1 and Table 2 respectively.

Table 1. Chemical compositions (wt.%)

Elements	AA6101T-6	AA1350
Al	97.50	99.50
Si	0.60	0.08
Fe	0.35	0.36
Cu	0.10	0.02
Mn	0.10	0.01
Mg	0.90	Nil
Zn	0.10	0.01
Ti	0.10	0.01
Cr	0.10	Nil
V	Nil	0.01
Others	0.15	Nil

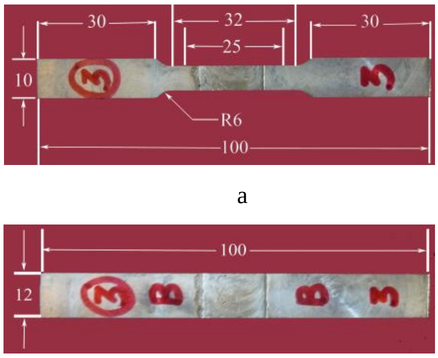
Table 2. Mechanical properties

Base Metals	AA6101T-6	AA1350
Ultimate Tensile Strength, MPa	136	60
Elongation, %	38.50	25.77
Bending strength, MPa	29	13
Hardness, HV	69	39

AA6101-T6 and AA1350 Al alloys were placed at advancing and retreating side respectively. The side, on which tool rotation and travelling are in the same direction is known as advancing side. If they are in counter direction, then it is known as retreating side. The plates were clamped tightly over the bed to avoid displacement or vibration during welding. Single pass welding method was adopted for fabricating the weld joints.

All the butt welded joints were made of hexagonal pin profiled high speed steel (HSS) tool with 15 mm shoulder diameter, 5 mm pin diameter and 5.6 mm pin length as it was found to be the best tool profile earlier [14]. During welding, axial load was constant in such a manner that tip of the tool pin was always 0.4 mm away from the lower surface of base metals. For welding, 4-axis computer controlled friction stir welding machine, with an accuracy of ± 6 microns, was used. Tool rotational speed, traversing speed and tilt angle were selected as welding parameters for friction stir welding. The range of tilt angle that can be varied against the direction of welding in 4-axis FSW machine was from 0° to 2°. Hence, in the present work, the welding parameters are selected in such manner as to attain satisfactory joint efficiency [15, 16].

After welding, mechanical and metallurgical tests were carried out for each specimen. To characterize the mechanical properties of each weld, tensile, bending and hardness tests were employed. Tensile and bending specimens were cut perpendicular to the direction of weld by Wire cut EDM machine as per ASTM E8M-04 and ASTM E290-08 standards respectively (Fig. 1). Both tests (Fig. 2) were performed by computer controlled 5 Ton (Associated scientific engineering works) universal testing machine, with an accuracy of ± 1 %.



b

Fig. 1. Photographs: a – tensile specimen (ASTM E8M-04 standard); b – bending specimen (ASTM E290-08 standard)

a b

Fig. 2. Photographs: a – tensile specimen (after tensile test); b – bending specimen (after bending test)

The hardness tests were done at various points along the welded region by using Wilson Wolpert micro Vickers hardness tester. For the purpose of microstructural analysis, each specimen was polished and etched with Keller's reagent solution and scanned in a De-winter inverted trinocular metallurgical microscope.

3. TAGUCHI TECHNIQUE

Genichi Taguchi [17] developed the Taguchi technique in 1980. This technique is a simple and powerful technique, which can optimize the performance characteristics within the combination of process parameters. Aykut Canakci et al [18] employed Taguchi technique and ANOVA to determine the effect of process parameters on particle size and optimal milling parameters in milling. Koilraj et al [19] used Taguchi L_{16} orthogonal array and ANOVA for optimizing the welding parameters to improve the tensile strength of friction stir welded joints of dissimilar AA2219-T87 and AA5083-H321 plates. In this present work, Taguchi L_9 orthogonal array was chosen for analyzing the effects of welding parameters on output factors. Tool rotational speed, traversing speed and tilt angle were considered as controlled variables and tensile strength, micro hardness and bending strength were considered as output factors. The welding parameters and their levels are shown in Table 3.

Table 3. Levels of welding parameters

Welding parameters	Level 1	Level 2	Level 3
A – Rotating speed, rpm	765	910	1070
B – Traversing speed, mm/min	78	100	120
C – Tilt angle, °	0	1	2

3.1. Signal to noise ratio

The terms signal (*S*) and noise (*N*) represent desirable and undesirable effect for the output characteristic respectively. Deviation of quality characteristics from desired values are measured by *S/N* ratio. Three types of *S/N* ratio characteristics are Nominal the better, larger the better and lower the better. Since higher tensile strength, micro hardness and bending strength are desirable, the larger the better *S/N* quality characteristic was employed in this investigation. *S/N* ratio for the larger the better is calculated by the Eq. 1.

$$\frac{S}{N} = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \qquad (1)$$

where n is the number of replications and y_i is observed response value. The observed experimental results and calculated *S/N* ratio values are given in Table 4. The analyses were done using MINITAB 17. The largest *S/N* ratio value provides the optimum level. Hence, the best combination of welding parameters for the tensile strength were A3B1C3. Thus, the optimal welding parameters for maximizing tensile strength were found to be rotational speed of 1070 rpm, traversing speed of 78 mm/min and tilt angle of 2°. From response table for Signal to Noise Ratios shown in Table 5, most influencing welding parameter for tensile strength was tool rotational speed.

Table 5. Response table for signal to noise ratios for tensile strength

Level	Rotating speed, rpm	Traversing speed, mm/min	Tilt angle, °
1	35.11	35.86	35.77
2	36.17	35.93	35.56
3	36.15	35.65	36.10
Delta	1.05	0.28	0.54
Rank	1	3	2

Table 6. Response table for signal to noise ratios for hardness

Level	Rotating speed, rpm	Traversing speed, mm/min	Tilt angle, °
1	33.12	34.02	34.14
2	34.45	34.22	33.65
3	34.44	33.77	34.23
Delta	1.33	0.45	0.59
Rank	1	3	2

Table 7. Response table for signal to noise ratios for bending strength

Level	Rotating speed, rpm	Traversing speed, mm/min	Tilt angle, °
1	23.70	23.90	24.08
2	23.06	23.25	23.51
3	23.70	23.31	22.86
Delta	0.63	0.65	1.22
Rank	3	2	1

The perfect combination of welding parameters for micro hardness were A3B1C3. Thus, the optimal welding parameters for maximizing hardness were rotational speed of 1070 rpm, traversing speed of 78 mm/min and tilt angle of 2°. From response table for Signal to Noise Ratios shown in Table 6, most influencing welding parameter for micro hardness was tool rotational speed.

For bending strength, *S/N* values for the experiments 1, 2, 6, 7 and 8 were same. Out of five experiments, largest *S/N* ratio values for tensile strength and bending strength were observed in experiments 7.

Table 4. Taguchi L_9 (3^3) orthogonal array

Experiment	A	B	C	Ultimate Tensile Strength		Micro hardness		Bending strength	
				Result, MPa	*S/N* ratios, dB	Result, HV	*S/N* ratios, dB	Result, MPa	*S/N* ratios, dB
1	1	1	1	55	34.8073	43.3	32.7298	16	24.0824
2	1	2	2	58	35.2686	46.9	33.4235	16	24.0824
3	1	3	3	58	35.2686	45.8	33.2173	14	22.9226
4	2	1	2	63	35.9868	51.3	34.2023	15	23.5218
5	2	2	3	65	36.2583	52.2	34.3534	12	21.5836
6	2	3	1	65	36.2583	54.9	34.7914	16	24.0824
7	3	1	3	69	36.7770	57.1	35.1327	16	24.0824
8	3	2	1	65	36.2583	55.5	34.8859	16	24.0824
9	3	3	2	59	35.4170	46.3	33.3116	14	22.9226

So, the perfect combination of welding parameters for bending strength was A3B1C3. Thus, the optimal welding parameters for maximizing bending strength were rotational speed of 1070 rpm, traversing speed of 78 mm/min and tilt angle of 2°. From response table for Signal to Noise Ratios shown in Table 7, most influencing welding parameter for bending strength was tool tilt angle.

3.2. ANOVA

Analysis of variance (ANOVA) was performed for the 95 % level of confidence to determine the percentage contribution of each control variable on tensile strength, hardness and bending strength of welding joints. ANOVA analyses are tabulated in Table 8 to Table 10. According to the Table 8, tool rotating speed, traversing speed and tilt angle influenced the tensile strength values by 64.45 %, 4.13 % and 14.51 % respectively. From the analysis, it is observed that tool rotating speed was the most significant factor on the tensile strength because percentage contribution (PCR) was very high.

Table 8. ANOVA for tensile strength

Factors	DF	SS	MS	F ratio	P value	PCR, %
A	2	107.56	53.78	5.44	0.045	64.45
B	2	6.89	3.44	0.13	0.881	4.13
C	2	24.22	12.11	0.51	0.625	14.51
Error	2	28.22	14.11			16.91
Total	8	166.89				
DF: Degree of freedom, SS: Sum of squares, MS: Mean of squares, PCR: Percentage of contribution.						

According to the Table 9, tool rotating speed, traversing speed and tilt angle influenced the hardness values by 58.24 %, 5.02 % and 11.29 % respectively. From the results, it is observed that rotating speed was the most significant factor in affecting the hardness at weld center.

Table 9. ANOVA for hardness

Factors	DF	SS	MS	F ratio	P value	PCR, %
A	2	114.05	57.02	4.18	0.073	58.24
B	2	9.81	4.91	0.16	0.857	5.02
C	2	22.11	11.05	0.38	0.698	11.29
Error	2	49.85	24.93			25.45
Total	8	195.82				

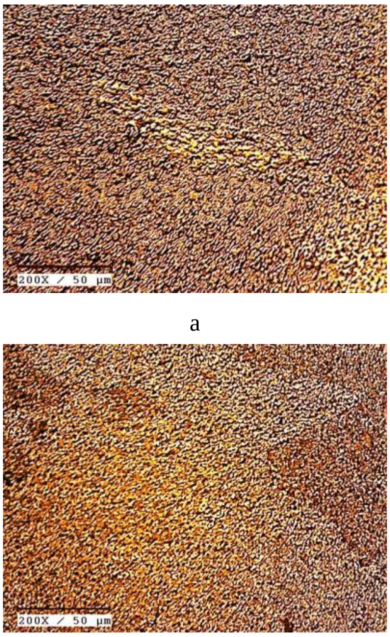
According to Table 10, most significant factor for bending strength was the tool tilt angle with a percentage contribution of 37.50 %. From the results, it is observed that rotating speed and traversing speed had equal significance on the bending strength with a percentage contribution of 12.50 %.

Table 10. ANOVA for bending strength

Factors	DF	SS	MS	F ratio	P value	PCR, %
A	2	2.00	1.00	0.43	0.670	12.50
B	2	2.00	1.00	0.43	0.670	12.50
C	2	6.00	3.00	1.80	0.244	37.50
Error	2	6.00	3.00			37.50
Total	8	16.00				

4. RESULTS AND DISCUSSION

Fig. 3 a shows the microstructure of AA1350 alloy. It shows the grain size varying from 10 µm to 20 µm. Fig. 3 b shows the microstructure of AA6101-T6 alloy. It shows the grain size varying from 5 µm to 10 µm. Increment in rotating speed increases frictional heat generation in weld region [20]. Increase of tilt angle increases the compressive force of tool shoulder in trailing direction on weld plates which results in higher heat generation [21]. Increment in traversing speed promotes higher rate of cooling [22]. Tensile and bending tests were conducted to evaluate the bond strength of welding.



a

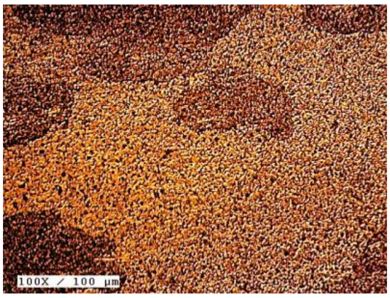
b

Fig. 3. Optical microstructures: a – AA1350 aluminium alloy; b – AA6101-T6 aluminium alloy

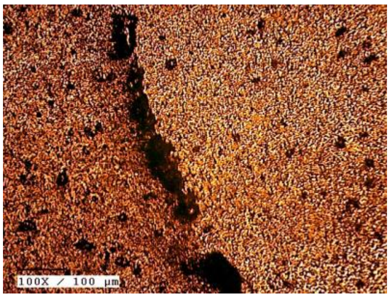
The sample fabricated by the combination of higher rotating speed of 1070 rpm, lower traversing speed of 78 mm/min and higher tilt angle of 2° exhibits highest tensile strength (69 MPa) and highest bending strength (16 MPa). Tensile and bending strengths are 15 % and 23 % higher than AA1350 aluminium alloy. Higher rotating speed and higher tilt angle result in high heat input to welding process. Slow traversing speed results in lower rate of cooling. Combination of higher rotating speed and lower traversing speed promotes sufficient interaction time of tool with weld plates, which encourages perfect transportation and mixing of materials from advancing side to retreating side and retreating side to advancing side. Hence, finer grains with uniform distribution (Fig. 4 a) has been obtained in the weld region, which encourages the formation of defect free weld (Table 11).

The sample fabricated by the combination of lower rotating speed of 765 rpm, lower traversing speed of 78 mm/min and tilt angle of 0° exhibits lowest tensile strength (55 MPa). Lower rotating speed and tilt angle of 0° result in low heat input to welding process. The rate of cooling is same as that of previous one. Reaction between materials in the stir zone mainly depends on amount of heat generation. Insufficient heat generation during welding process affects the breaking and distribution of particles in the weld region, which results in insufficient transportation and improper mixing of material (Fig. 4 b). Hence, volume defects (Table 11) have been observed in the weld region, which lower the tensile strength of weld joint.

a



b



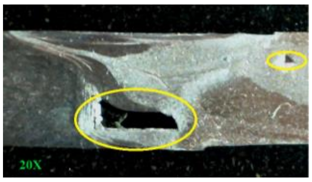
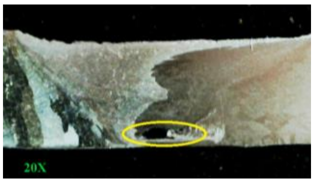
c

Fig. 4. Optical microstructures: a – sample fabricated by 1070 rpm, 78 mm/min and 2°; b – sample fabricated by 765 rpm, 78 mm/min and 0°; c – sample fabricated by 910 rpm, 100 mm/min and 2°

The sample fabricated by the combination of medium rotating speed of 910 rpm, medium traversing speed of 100 mm/min and higher tilt angle of 2° exhibits lowest bending strength (12 MPa). Due to reduced rotating speed, heat input is somewhat lower when compared to experiment 7. The heat input due to tilt angle was same as that of experiment 7. Due to increased traversing speed, rate of cooling is somewhat higher when compared to experiment 7. Combination of reduced rotating speed and increased traversing speed lowers the interaction time of tool with weld plates which affects the transportation of material and degree of consolidation. Hence, more discontinuities have been observed (Fig. 4 c and Table 11) in the weld region, which affect the bending strength of weld joint.

Fig. 5 shows the distribution of hardness across the weld. It indicates that hardness values at weld center are higher than retreating and advancing sides. The sample fabricated by the combination of higher rotating speed of 1070 rpm, lower traversing speed of 78 mm/min and higher tilt angle of 2° exhibits highest hardness value at weld center.

Table 11. Macrostructures of joint cross sections

Experiment	Macrograph of the joint cross section	Quality of weld
1		Poor
4		Poor
5		Poor
7		Good (defect free)

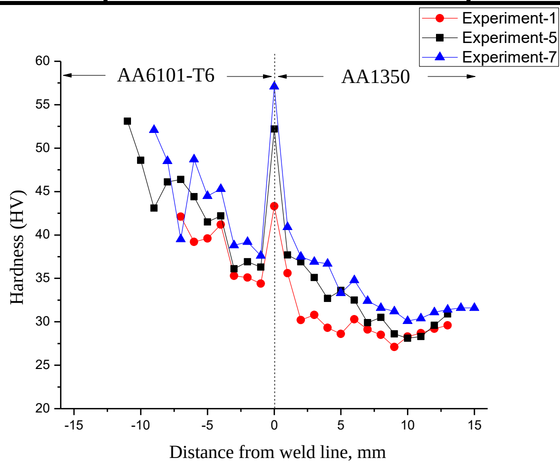


Fig. 5. Hardness distribution across the weld

This is because of finer grains and strengthening precipitates (Mg_2Si). Highest hardness value observed at weld center is lower than hardness value of AA6101-T6 and higher than AA1350. Hardness values at advancing side are higher than retreating side. Hence, during tensile testing, fractures have occurred at retreating side. Minimum hardness values have been observed at Heat Affected Zone (HAZ) of retreating side. This is due to softening of Heat Affected Zone. Softening occurrence is directly related to annealing effect. Hence, all fractures have occurred at Heat Affected Zone of retreating side.

5. CONCLUSIONS

In this paper, the effects of tool rotating speed, traversing speed and tilt angle were analysed during friction stir welding of AA6101-T6 and AA1350 aluminium alloys using Taguchi technique. Defect free weld was observed at tool rotating speed of 1070 rpm, traversing speed of 78 mm/min and tilt angle of 2°. Signal to noise ratio was utilised to determine the most significant parameter on output factors. ANOVA was utilised to determine the contributions of each control variable on output factors. Most significant parameter on tensile strength and hardness were tool rotating speed. Tilt angle was the most significant parameter for bending strength. From microstructural analysis, it was observed that highest tensile and bending strength were obtained due to finer grains with uniform distribution. Improper mixing of material and discontinuities in weld region lower the tensile and bending strength. From Vickers micro hardness test, it was observed that highest hardness values were at weld center. During tensile testing, all fractures were observed at HAZ of AA1350 side.

Acknowledgments

The authors are grateful to the National Institute of Technology, Trichy for extending the lab facilities to conduct welding experiments. The authors would like to thank the management of K.L.N. College of Engineering for supporting to carry out this investigation.

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