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An Experimental Analysis and Optimization of Process Parameters on Friction Stir Welding of Dissimilar AA6061-T6 and AA6951-T6 Using Taguchi Technique

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Abstract - *Aluminum alloys are broadly used in aerospace industry, automotive industry, railways and in marine industry due to its resistance to corrosion, light weight and high strength to weight ratio. The aim of the present research is to optimize the process parameters for higher tensile strength and to analyze the effect of process parameters such as tool rotational speed, welding speed and tool tilt angle on the tensile strength of friction stir weldments. Taguchi L_9 orthogonal array was used to conduct the experiments. The optimum process parameters for the maximum tensile strength of the joints were predicted, and the individual significance of each process parameter on the tensile strength of the friction stir weldment was evaluated by using the signal-to-noise ratio and analysis of variance (ANOVA) results.*

***Key Words*: Friction Stir Welding, Dissimilar Joining, Rotational Speed, Welding Speed, Tool Tilt Angle, Tensile Strength**

1. INTRODUCTION

The dissimilar joining of metals with different thermo-mechanical and chemical properties is often more challenging as it results in the formation of brittle intermetallic compounds. Joining of aluminum (Al) or its alloys with copper (Cu) is preferred in many applications in engineering [1].

In aircraft and automotive structures friction stir welded lap joints have been widely used with the aim to replace riveted lap joints by using aluminium alloys. Rivet holes are often potential sites for crack initiation or corrosion problems; moreover, the elimination of fasteners leads to considerable weight and cost savings. A few examples of FSW joints applied in automotive industries are some applications include engines, wheel rims and lap joints in car back supports

Friction Stir Welding (FSW) is a solid welding process invented by The Welding Institute (TWI) in 1991 [2]. In the Friction Stir Welding process, a non-consumable, rotating tool with a specific geometry is plunged into and traversed through the material. The two key components of the tool are the shoulder and the pin (probe). During welding, the pin travels in the material, while the shoulder rubs along the surface. Heat is generated by the tool shoulder rubbing on the surface and by the pin mixing the material below the shoulder. This mixing action permits the material to be transferred across the joint line, allowing a weld to be made without any melting of the material.

1.1 Principle of Friction Stir Welding

Friction Stir Welding is a solid-state process, which means that the objects are joined before reaching the melting point. In FSW process, a cylindrical-shouldered tool, with a profiled probe (nib or pin) is rotated at a constant speed and fed at a constant traverse rate into the joint line between two pieces of sheet or plate material. The parts to be joined are clamped rigidly in order to prevent the joint faces from being forced apart. The tool pin length is kept slightly less than the weld depth required so that there should be an intimate contact of shoulder with the work surface.

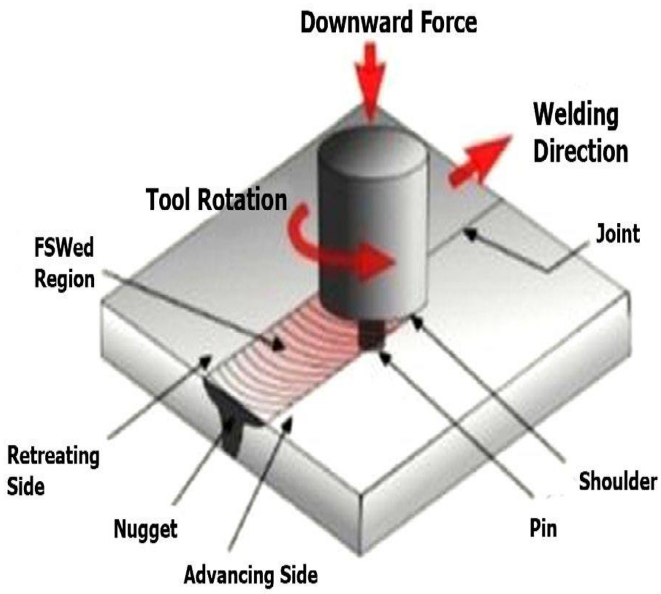

Fig -1: Principle of friction stir welding [3]

There is a generation of frictional heat between the wear-resistant welding tool shoulder and nib, and the material of the work pieces. This generated heat, along with the heat generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without reaching the melting point. As the pin is pushed toward welding, the primary face of the pin, assisted by an exceptional pin profile, forces plasticized material to the back of the pin while applying an substantial forging force to consolidate the weld metal. The welding of the material is empowered by plastic deformation in the solid state.

2. EXPERIMENTAL DETAILS

The material used for the research work was aluminum alloy AA6061-T6 and AA6951-T6 of 6mm thick sheets. The chemical and mechanical properties of the material are shown in table 1 and table 2 respectively.

Table -1: Chemical properties of AA6061 and AA6951

Element	Weight %	
	AA6061-T6	AA6951-T6
Si	0.7	0.399
Mg	0.99	0.398
Cu	0.21	0.115
Mn	0.12	0.0427
Zn	0.088	0.268
Cr	0.6	0.0173
Al	Remaining	Remaining

Table -2: Mechanical properties of AA6061 and AA6951

Properties	AA6061-T6	AA6951-T6
Tensile Strength MPa	360	270
Yield Strength MPa	276	230
Hardness HRB	60	50
Elongation %	17	13

The friction stir welding was performed on vertical milling machine shown in figure 2. Welds were made by joining two (110 x 75 x 6) mm plates to make a weld joint of size 150 mm wide and 110 mm long.

Fig -2: Friction stir welding on vertical milling machine

In this investigation a tapered threaded cylindrical tool was used. The tool was made up of H-13 Steel with a shoulder diameter of 18mm and 5.8mm pin length. The threaded cylindrical pin was tapered from the root diameter of 6 mm to the top diameter of 4.8 mm as shown in figure 3. The three parameters such as rotational speed, transverse speed and tool tilt angle are taken into consideration, the parametric rage and their levels are listed in Table 3.

Fig -3: Friction stir welding tool

Table -3: Process parameter and their levels

Parameters	Level 1	Level 2	Level 3
Rotational speed (rpm)	1540	1950	2300
Welding speed (mm/min)	25	35	35
Tool tilt angle (degree)	0	0.5	1.0

2.1 Taguchi's Method

The Taguchi method was used to optimise the welding parameters. This method is a time-saving technique to optimise the process parameters. In this method, an appropriate orthogonal array should be selected depending on the total degree of freedom (DOF). The degree of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. So, L_9 orthogonal array was selected which has a degree of freedom of 8. Nine experimental runs were conducted as per Taguchi L_9 orthogonal array.

2.2 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) test was performed to identify the process parameters that are statistically significant. The purpose of the ANOVA test is to investigate the significance of the process parameters which affect the tensile strength, impact strength and hardness of FSW joints. The results of ANOVA indicate that the considered process parameters are highly significant factors affecting the tensile strength, impact strength and hardness of FSW joints.

2.3 S/N Ratio

Taguchi also recommended analysing the valued using S/N ratio. It involves conceptual approach which graphs the effect and identifies the significant values.

$$n_j = -10\log\left(\frac{1}{n}\sum y_{ijk}^2\right)$$

where n is the number of tests and $Yijk$ is the experimental value of the i^{th} quality characteristics in the j^{th} experiment at the k^{th} test.
In this study, the S/N ratio was chosen according to the criterion of the larger the- better, in order to maximize the response.

Table -4: Taguchi's L_9 orthogonal array

Sr. No.	Rotational speed	Welding speed	Tool tilt angle
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

2.4 Tensile Testing of the Weld Joints

All weld joints were prepared as per the design matrix and test specimens from these joints were prepared for mechanical testing. The weldments are shown in figure 4.

Fig -4: Friction stir weldments

Trial experiments were conducted to determine the working range of welding parameters. The initial joint configuration was obtained by securing the plates in position using mechanical clamps on FSW machine. Single pass welding procedure was followed to fabricate the joints.

Table -5: Experimental results for tensile strength

Sr. No.	Rotational Speed (rpm)	Welding Speed WS (mm/min)	Tool Tilt Angle (Degree)	Tensile Strength (MPa)	S/N Ratio
1	1540	25	0.0	124	41.86
2	1540	35	0.5	123	41.79
3	1540	45	1.0	119	41.51
4	1950	25	0.5	129	42.21
5	1950	35	1.0	140	42.92
6	1950	45	0.0	127	42.07
7	2300	25	1.0	130	42.27
8	2300	35	0.0	152	43.63
9	2300	45	0.5	131	42.34

Tensile test samples were prepared from welds joints according to the ASTM E-8 specification, Data from each weld specimens was recorded as values of yield strength, tensile strength and percentage elongation. A universal testing machine is used to test the tensile stress strength of material. It is named after the fact that it can perform many standard tensile and compression tests on materials, components, and structures.

Fig -5: Tensile test specimen

Table -6 Analysis of variance for S/N Ratio

Source	DF	Seq SS	Adj SS	F	P	Contri bution
RPM	2	377.5	377.5	5.2	0.16	47.30%
WS	2	278.2	278.2	3.8	0.20	34.85%
Angle	2	70.2	70.2	0.9	0.50	8.79%
Residu al Error	2	72.2	72.2			9.04%
Total	8	798.2				99.98

Table -7 Response Table for Signal to Noise Ratios (Larger is better)

Levels	RPM	WS	Angle
1	41.73	42.12	42.53
2	42.40	42.79	42.12
3	42.75	41.98	42.24
Delta	1.03	0.81	0.41
Rank	1	2	3

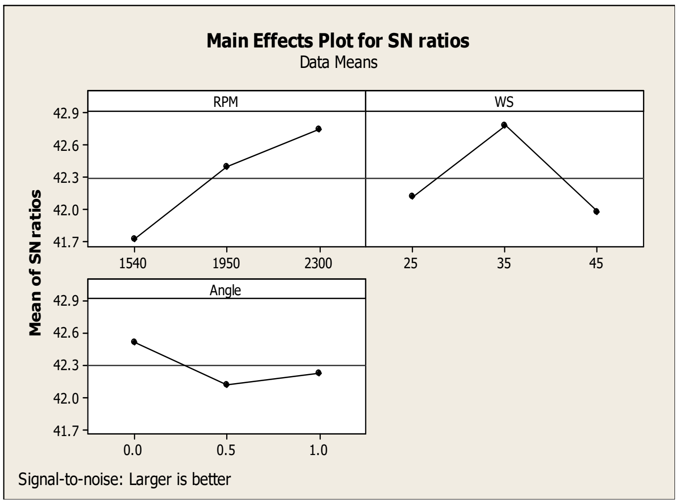

Fig -6: Represents the effect of parameters on S/N ratio of tensile strength

From figure 6 it is observed that the tensile strength of the weldment increases with the increase in the tool rotational speed. But in case of welding speed the tensile strength once increases and then decreases immediately. When the welding lies in between 25 mm/min to 35 mm/min tensile strength increases. On further increase in welding speed from 35 mm/min to 45 mm/min tensile strength decreases. It can be seen that with the increase in tool tilt angle the tensile strength decreases. When the tool tilt angle lies in between 0˚ to 0.5˚ tensile strength decreases slightly but on increasing the tool tilt angle from 0.5˚ to 1.0˚ the tensile strength a little increases.

From the table 7 and figure 6 it can be concluded that tool rotational speed of 2300 rpm, welding speed of 35 mm/min and tool tilt angle 0˚ is the optimum welding condition to get a higher tensile strength.

Interaction plot for tensile strength

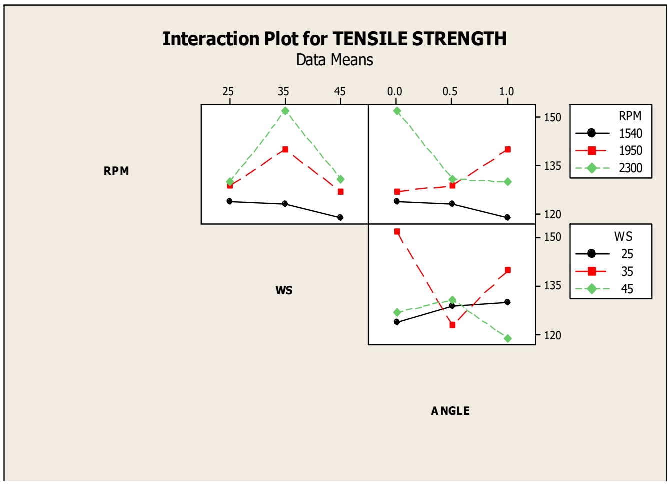

Fig -7: Interaction plot for tensile strength

Relationship between tool rotational speed and welding speed

When tool rotational speed is 1540 rpm and welding speed is in between 25 mm/min to 35 mm/min there is slight decrease in tensile strength. When welding speed is in between 35 mm/min to 45 mm/min. the tensile strength decreases. It can be seen that at 1950 rpm tool rotational speed and is in between 25 mm/min. to 35 mm/min welding speed there is increase in tensile strength. However, when welding speed lies between 35 mm/min to 45 mm/min the tensile strength decreases immediately. For 2300 rpm tool rotational speed and welding speed is in between 25 mm/min to 35 mm/min there is drastically increase in tensile strength. It can be seen that at welding speed between 35 mm/min to 45 mm/min the tensile strength decreases sharply.

Relationship between tool rotational speed and tool tilt angle

At tool rotational speed of 1540 rpm and tool tilt angle is lies in between 0˚ to 0.5˚ there is slight decrease in tensile strength and when tool tilt angle is in between 0.5˚ to 1.0˚ the tensile strength decreases. For 1950 rpm tool rotational speed and tool tilt angle is in between 0.5˚ to 1.0˚ there is immediately increase in tensile strength and when tool tilt angle is in between 0.5˚ to 1.0˚ the tensile strength decreases. It is observed that when tool rotational speed is 2300 rpm and tool tilt angle lies in between 0.5˚ to 1.0˚ there is drastically decrease in tensile strength. Also when the tool tilt angle is lies in between 0.5˚ to 1.0˚ the tensile strength decrease slightly.

Relationship between welding speed and tool tilt angle

It can be seen from figure 7 when tool welding speed is 25 mm/min and tool tilt angle is in between 0.5˚ to 1.0˚ there is slightly increase in tensile strength. With the increase in the angle from 0.5˚ to 1.0˚ the tensile strength increase a little. When welding speed is 35 mm/min and tool tilt angle is in between 0.5˚ to 1.0˚ there is slightly increase in tensile strength. By increasing the tool tilt angle from 0.5˚ to 1.0˚ the tensile strength increases drastically. For welding speed of 25 mm/min and tool tilt angle is in between 0.5˚ to 1.0˚ there is extremely decrease in tensile strength. And when tool tilt angle is in between 0.5˚ to 1.0˚ the tensile strength decrease a little.

3 CONCLUSIONS

In the present study FSW was used for developing butt joints between dissimilar AA6061-T6 and A6951-T6 Al alloys at a constant axial load of 6 kN and various traverse welding speeds of 25, 35 and 45 mm/min, various tool rotational speed of 1540, 1950 and 2300 rpm and at different tool tilt angles of 0˚, 0.5˚ and 1.0˚. In this study, the Taguchi method was used to obtain optimal condition for Friction Stir Welding of AA6061-T6 to AA6951-T6 aluminium alloy. Experimental results were evaluated using ANOVA. From the tensile strength investigations the following conclusions can be drawn:-

1. A maximum tensile strength was exhibited by the friction stir welded joints fabricated with the optimized parameters of 2300 r/min rotational speed, 35 mm/min welding speed and tool tilt angle 0˚.

2. Tool rotational speed plays a vital role and contributes 47.30% to the overall contribution and welding speed & tool tilt angle have 34.85%, 8.79% influence on tensile strength of joint respectively.

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