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Optimization of the Process Parameters of Friction Stir Welded Aluminum Alloys for Maximum Tensile Strength

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Abstract: *The friction stir welding (FSW) process is an innovative technique to join metals in the plastic state thus not reaching the liquid state as it happen in traditional welding process. This feature of the FSW proved that a modification can be done on the fatigue behavior and strength of the welding joints so, some of the leading companies are adopted this process for the manufacturing of Automotive, locomotive, shipping & aerospace. Experiments are conducted here, with a tool having a tapered square tool pin of 0.3mm clearance. The process parameters are optimized by using Taguchi technique based on Taguchi's L_9 orthogonal array. Experiments have been conducted based on three process parameters, namely, the tool rotational speed, tool tilt angle and travel speed. Tensile strength has been predicted for the optimum welding parameters and their percentage of contribution in producing a better joint is calculated, by applying the effect of the signal-to-noise ratio and analysis of Variance. Based on the study, the tool tilt angle is found to be the most significant variable over the other process parameters. The optimum tensile strength predicted through ANOVA is 285MPa.*

Keywords: *FSW, Aluminum Alloys, Tensile strength. Taguchi technique*

I. Introduction

Friction stir welding (FSW) [1] is solid state thermo- mechanical joining process in which bonding between two parts occurs by severe plastic deformation of adjacent interfaces under conditions of hydrostatic pressure. Peak temperature during FSW process may be well below the melting temperature of welded material, lessening typical undesirable effect of welding processes. This joining technique is an excellent choice for aluminum alloys which are used in aerospace and automotive applications due to some of its outstanding qualities such as, better dimensional stability, preservation of base material properties, resistance to hot cracking etc.[2-4].

In FSW, a non- consumable rotating tool moves along the weld seam with a pin immersed into the work-piece. The conventional FSW tool is comprised of (a) shoulder and (b) pin, where the shoulder predominantly generates frictional heat and prevents the expulsion of material from the weld zone. The role of FSW tool pins is to provide sufficient plastic deformation to cause bonding across any pre-existing interfaces while transporting material to positions behind the tool. Right after the invention of friction stir welding by TWI in 1991, efforts have been made towards designing FSW tool pins [1, 5-9] in order for the process to be flourished over a range of manufacturing applications. However, tool geometry studies are necessarily limited as the potential variation in geometry is essentially infinite. Since instinctive perceptions are employed for most of the tool designs which are typically based on empirical knowledge [10], process parameters and tool parameters may vary greatly in FSW of aluminum alloys. Consequently, numerous efforts have been devoted to understand the relationship between tool parameters (including geometric shape, dimensions and thread features) and mechanical-microstructure properties of different alloys within a wide range of welding conditions [11-16]. FSW tool pins are often featured with thread forms. A complex pin is designed with thread forms having different thread interruptions such as flats or flutes [9, 15-17]. However, vertical movements of material during FSW were presumed to be predominated by helical features in tool pin [18-19]. Tool pin geometries and features are one of the important process control parameters in FSW that influence material flow which in turn affect joint efficiency. Differences between base metal properties of different aluminum alloys also contribute to different material flow and different process response variables for identical friction stir welding control parameters including tool geometry. Considering medium strength 6xxx series and high strength 7xxx series aluminum alloys, resistances to deformation of 6xxx alloys are less compared to 7xxx series alloy while thermal conductivity is greater for the lower alloyed 6xxx series. These properties lead to a weldability advantage of 6xxx over 7xxx series alloys.

II. Taguchi Method

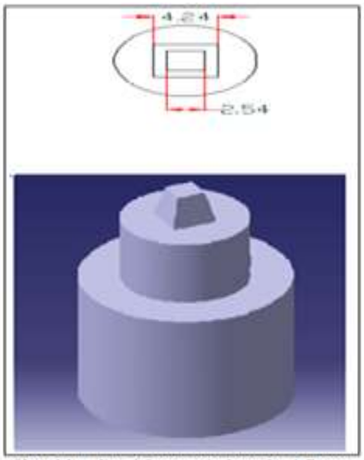
The Taguchi method is very effective, because it is simple to carry on the design and its approach is very systematic to provide good quality and low cost in manufacturing [20]. The main aim of the Taguchi method is to analyze the statistical data, which has been given as an input function to produce an optimum result. The effect of the combination of the input functions as a result is produced by the S/N ratio and mean response [21]**.** The strength of the weld is varied by the parameters such as the tool rotating speed, tool tilt angle, depth of penetration, dwell time and travel speed. Among these input parameters, rotating speed, tool tilt angle and travel speed are taken and the other parameters are maintained constant. The input parameters are entered in the array table with the output characteristics as the average tensile strength. Hence the Taguchi technique is applied to a self analysis of the high strength material based on the tensile strength.

MINITAB software is used for the statistical analysis, how to form a combination of input parameters and to find out most significant combination [22]. Process parameters are control factors which initiate variability in the process are the noise factors. In a Taguchi designed experiment, the noise factors are manipulated for the variability to occur, and from the results optimal control factors that make the process robust, can be identified. The Signal to Noise ratio (S/N) indicates the control factors settings that minimize the effect of the noise factors.

The Taguchi method has been implemented using MINITAB software, which includes the S/N ratio and ANOVA. Through ANOVA the contribution of the individual parameter in making better FSW welds can be identified. The response for the signal to noise ratio gives the most influencing parameter. Through the mean plots of the S/N ratio and mean response, the optimum parameter has been identified.

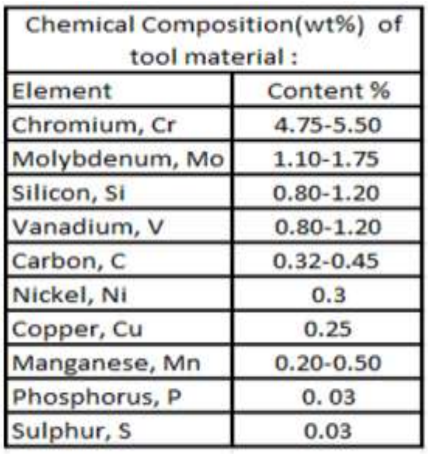
III. Material and Experimental Work

The present investigation uses a IS:65032-T6 aluminum alloy, and find its application in aerospace as structural members and storage tanks. The rolled plates of 5mm thickness, IS:65032-T6 aluminum alloy, have been cut into the required size 150mm x 100mm by power hack saw cutting and milling. Square butt joint configuration has been prepared to fabricate the FSW joints. The initial joint configuration is obtained by securing the plates in position using mechanical clamps. The direction of welding is normal to the rolling direction. Single pass welding procedure has been followed to fabricate the joints. A non-consumable tool has been made of H13 tool steel used to fabricate the joints its dimensions are shown in Fig.1. The chemical composition of tool material and the base material are presented in Table.1 & 2 respectively. The position controlled Friction Stir Welding machine was used to fabricate the joints.



Shoulder dia: 16mm, pin length: 4.7mm

Fig.1. Tapered square tool pin



Chemical Composition(wt%) of tool material :	
Element	Content %
Chromium, Cr	4.75-5.50
Molybdenum, Mo	1.10-1.75
Silicon, Si	0.80-1.20
Vanadium, V	0.80-1.20
Carbon, C	0.32-0.45
Nickel, Ni	0.3
Copper, Cu	0.25
Manganese, Mn	0.20-0.50
Phosphorus, P	0. 03
Sulphur, S	0.03

Table.1. Chemical composition of tool material

Table.2. The chemical composition of base metal

Al	Cu	Mg	Si	Fe	Mn	Zn	Ti	Cr
97.100	0.224	0.916	0.545	0.534	0.362	0.245	0.016	0.005

According to the L_9 orthogonal array three experiments in each set of process parameters have been performed on IS:65032-T6 plates. The three factors used in this experiment are the rotational speed, tool tilt angle and travel speed. The factors and the levels of the process parameters are presented in Table.3 and these parameters are taken based on the trials to weld the FSW of aluminum alloys. The experiment notation is also included in the L_9 orthogonal array which results in additional column, in order to represent the parameters, as presented in Table.4. The experiments are performed on a FSW machine, it is a well known factor at higher rotating speed, FSW produces high heat input and these three levels were selected as low, medium, and high speed. Beyond the tool tilt angle of 2° the pin pierces out the plasticized material for the thickness of 3mm and hence 0°, 1° and 2° tool tilt angle were taken. The FSW butt joint weld being performed on a aluminum plates needs careful experimentation, and hence the tool is plunged slowly into the work piece, till the tool shoulder comes in contact with the surface of the work piece. When the tool is inserted the stirring action starts to occur, and only the pin penetrates deep into the work piece while tool shoulder touches the top surface. Frictional heat occurs along with the stirring action. Twenty seconds dwell time is given before start of each welding, and then automatic feed is given. According to the guidelines of American Society for Testing of Materials(ASTM) the tensile specimens are prepared as shown in Fig.2. The tensile tests for 18 specimens are conducted and they yielded a variety of results. A sample tensile specimen, before and after the failure as shown in Fig.3. (a) & (b). Most of the specimens tensile failure occurred in between the regions of HAZ and the base metal. FSW joints of aluminum alloy have been welded, and the average tensile strength of the two specimens from the same joint was obtained and is presented in Table.5. It reveals that the FSW parameters do not lead to a significant variation, and hence, the ANOVA is used to find the optimum process parameter.

Table.3. Factors and the Levels of the process parameters

Factors	Levels		
	1	2	3
A, Rotational speed (rpm)	1000	1300	1600
B, Tool tilt angle (°)	0	1	2
C, Travel speed (mm/min)	60	80	100

Table.4. Experimental layout of L_9 Orthogonal array

SI No.	Experiment's notation	Friction stir welding parameters level		
		A Rotational speed (rpm)	B Tool tilt angle (°)	C Travelspeed (mm/min)
1	A1	1	1	1
2	A2	1	2	2
3	A3	1	3	3
4	B1	2	1	2
5	B2	2	2	3
6	B3	2	3	1
7	C1	3	1	3
8	C2	3	2	1
9	C3	3	3	2

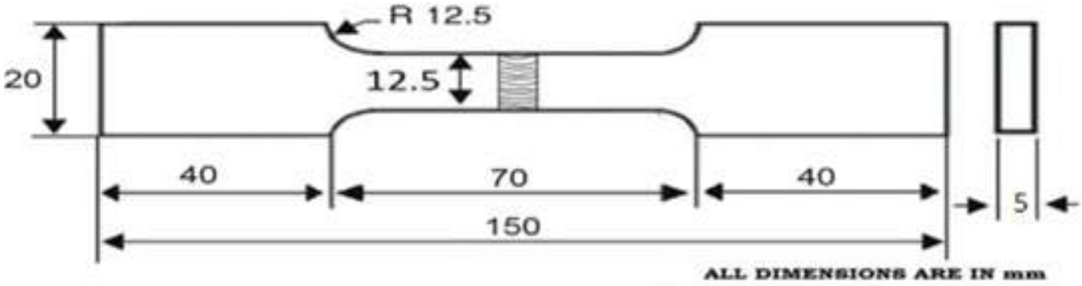


Fig.2. Tensile test specimen (ASTM E8M-04)

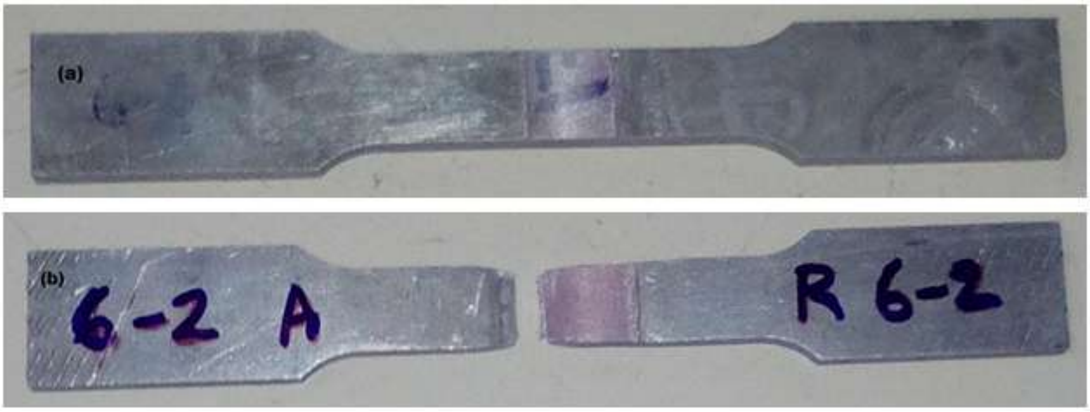


Fig.3. Tensile specimen (a) before failure (b) after failure

Table.5. The input parameter of orthogonal array and the output characteristics

Experimental number	Input Parameters			Output characteristic
	Rotational speed (rpm)	Tool tilt angle (°)	Travel Speed (mm/min)	Average tensile strength(MPa)
A1	1000	0	60	275
A2	1000	1	80	279
A3	1000	2	100	274
B1	1300	0	80	276
B2	1300	1	100	278
B3	1300	2	60	282
C1	1600	0	100	271
C2	1600	1	60	284
C3	1600	2	80	277

IV. Results and discussion

3.1 Mean and Signal to Noise ratio

The Mean and signal to noise ratio are the two effects which influence the response of the factors. The influencing level of each selected welding parameter can be identified. The tensile strength of the FSW weld is taken as the output characteristic. The response table for the S/N ratio shows that the tool tilt angle ranks first in the contribution of good joint strength, while travel speed and rotational speed take the second and third ranks. The same trend has been observed in the response table of the mean which is presented in Tables.6 &7 respectively. The response plots for the S/N ratio and mean are shown in Fig. 4 & 5. The tensile strength is estimated to be the maximum at1300 rpm rotation speed, 1° tool tilt angle and 60 mm/min travel speed; which is optimal from the plots obtained.

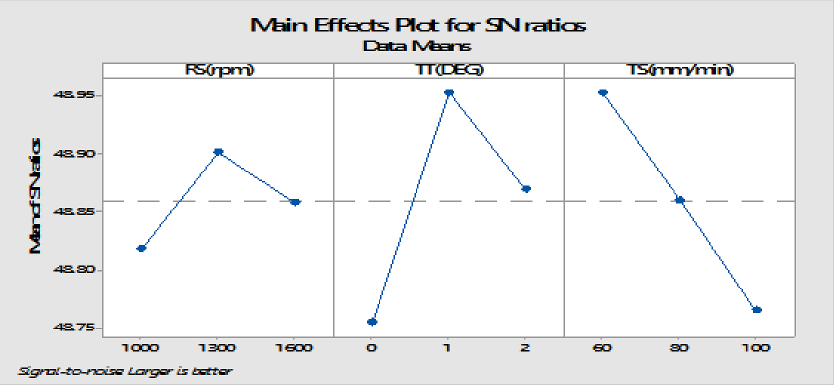


Fig.4. Main effect plot for S/N ratio

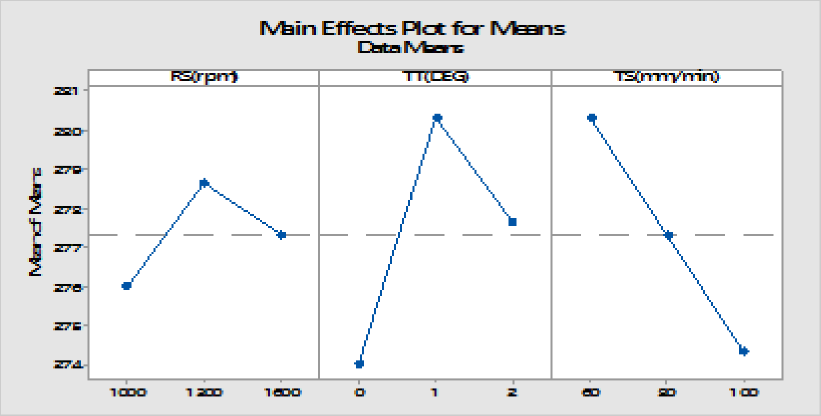


Fig.5. Main effect plot for Mean

Table.6. Response table for Signal to Noise Ratio

Level	Rotational speed	Tool tilt angle	Travel speed
1	48.82	48.75	48.95
2	48.90	48.95	48.86
3	48.86	48.87	48.77
Delta	0.08	0.20	0.19
Rank	3	1	2

Table.7. Response table for Mean

Level	Rotational speed	Tool tilt angle	Travel speed
1	276.0	274.0	280.3
2	278.7	280.3	277.3
3	277.3	277.7	274.3
Delta	2.7	6.3	6.0
Rank	3	1	2

3.2 Analysis of Variance

ANOVA is done in MINITAB software. The main aim of the analysis is to estimate the percentage of the individual contribution of the welding parameter on the tensile strength of the weld, and also give accurately the combination of the process parameters. Individual optimal values for the process parameters and their specified performance characteristics can be obtained. The relative importance of the welding parameters is presented in Table.8. The analysis of variance for tensile result shows that the tool tilt angle is the most significant parameter with a percentage of 47.39%, followed by the travel feed of 42.18% and rotation speed of 7.81%.

The optimum parameter obtained can be due to the two following possibilities; either the combination of the process parameters as prescribed may be present in the experimental combination, or may not be present in the combination. The optimum parameter for higher tensile strength obtained by the Taguchi method is presented in Table.9. With the tool tilt angle the material is pushed and stirred along the path of travel direction, but without the tool tilt angle only the normal stirring action takes place. Inclination of the tool thus helps to provide a good plastic deformation at the weld zone, and better material flow can be achieved. The combination of process parameters of 1300 rpm tool rotational speed, 1° tool tilt angle and 60 mm/min travel speed has been predicted under the ultimate tensile strength of 285MPa.

Table.8. Analysis of variance (ANOVA)

Source	DF	Adj. SS	Adj. MS	F	P	Percentage of contribution
Rotating speed	2	10.667	5.333	4.00	0.200	7.81
Tool tilt angle	2	60.667	30.333	22.75	0.042	47.39
Travel speed	2	54.000	27.000	20.25	0.047	42.18
Error	2	2.667	1.333			2.08
Total	8	128.000				

Table.9. Optimized result obtained from ANOVA – Minitab

	Rotational speed (rpm)	Tool tilt angle (°)	Travel speed (mm/min)	Ultimate tensile Strength (MPa)
Taguchi method	1300	1	60	285

3.3 Experimental result

The essential joint strength obtained from the optimization study is verified by conducting experiment, using the optimal combination of the process parameters (tool rotation speed 1300 rpm, 1° tool tilt angle and 60 mm/min traverse speed). An experiment is conducted with the optimum combination, and the average strength of the weld obtained with the process parameters is found to be 288MPa and this value is close to the predicted value. The ultimate tensile strength of the base material is 308MPa, hence the given set of parameters and levels Rotational speed 1300 rpm, 1° tool tilt angle and 60mm/min is the best condition to attain the maximum tensile strength.

When the process parameters are observed individually as per the contribution, each parameter shows a different characteristic behavior. If the rotating speed increases, then the rate of heat generation also increases in the stir zone. Then, the optimized value should be higher speed, but here it has resulted in a moderate speed, which indicates that sufficient heat alone is required for plasticized material flow. The tool tilt angle favors the material movement towards the travel direction and also the mixing of the plasticized material flow in the weld zone.

V. Conclusions

To find the optimal parameters the Taguchi technique has been used in this investigation. The following concluding remarks can be made from the present study:

- The Analysis of Variance for the tensile result concludes that the tool tilt angle is the most significant parameter with a percentage of 47.39% followed by the travel speed of 42.18% and rotation speed of 7.81%.
- The optimum combination of parameters obtained from the main effect plot for the S/N ratio and mean is 1300 rpm rotation speed, 1° tool tilt angle and 60 mm/min traverse speed, and the tensile strength has been

predicted as 285MPa. The confirmation test performed with the optimum process parameter is found to have an average tensile strength of 288MPa, and hence optimization is useful.

- The tool tilt angle favors the material movement towards the travel direction and also the mixing of the plasticized material flow in the weld zone, hence good mechanical and metallurgical properties of the weldments.

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