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Investigation of Friction Stir Welding parameters for Aluminium alloy 6061 by using Taguchi Method

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Abstract

Friction stir welding (FSW) is a relatively new & most significant solid-state welding technology used for welding similar and dissimilar materials without fusion or filler materials. FSW has inspired researchers and one of the most advanced topics for joining dissimilar materials. In the current study, weld joints of aluminium based alloy i.e. AA6061 are produced to optimize the process parameters of FSW using Taguchi's L9 orthogonal experimental design. The process parameters considered for conducting the experiments are; Tool rotation speed (rpm), welding speed (mm/min), and tool tilt angle (degree). The process response observed are; Ultimate tensile strength (UTS in MPa), and micro-hardness (Hv) of the attempted FSW weld required for the process under consideration. Initially, in the present work, the friction stir welding (FSW) of AA6061 has been conducted for enhancing its mechanical properties. The analysis of variance (ANOVA) test has been performed by using statistical software known as - "MiniTab 17.0" to reveal out the significant parameters and their contribution towards the output characteristics. From the analysis of S/N ratio, it has been revealed that at a tool rotational speed, welding speed, and tool tilt angle of: 1000 rev/min, 30 mm/min, and 3 degrees, respectively, the ultimate tensile strength is maximum, and for the maximum attainment of studied micro-hardness, the parameter's setting is as; tool rotational speed as 1000 rev/min, welding speed as 30 mm/min, and tool tilt angle as 2 degree. The optimized parameters values have also been attained to provide the studied process responses at their better levels.

Keywords: FSW; Taguchi; Aluminium; ANOVA; Modelling

1. Introduction

Friction stir welding (FSW) is an innovative green solid-state joining process in which coalescence takes place at temperatures below the melting point of the similar or dissimilar metals being joined and without use of a brazing filler metal with no harmful emissions. In 1991 a very potentially world beating welding method was discovered at The Welding Institute (TWI). FSW is especially suitable for joining sheets, plates, hollow pipes, etc. of Al alloys, sooner it was spread to many other materials like copper, magnesium, steels, zinc, titanium, etc. and their combinations. The process is widely used because it produces sound welds, weld metal experiences elevated temperature, large plastic deformation. However, the weld metal does not melt, which helps to avoid the oxidation of weld melt, gas pores, hot cracks and does not have common problems such as solidification and liquefaction cracking associated with the conventional welding techniques.

FSW is most significant & modernistic development in metal joining processes in a decade. Friction stir welding process uses a non-consumable rotating tool consisting of a pin extending below a suitable design shoulder that is forced into the adjacent mating edges of the work pieces & moved along the joint line as shown in Fig.1**.** The heat caused by high friction between the work piece and the tool that having forging action and stirring action result to induces intense local heating that does not melt the plates to joined hence, forming a thermo solid- state weld. In this process some special weld seam & filler wires are not required.

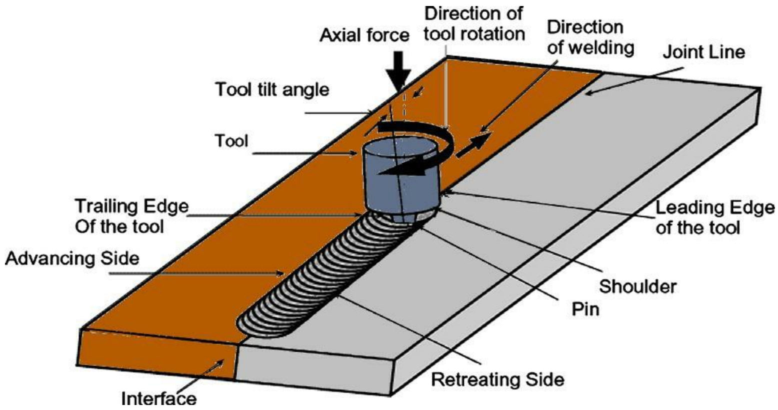


Figure 1. Schematic diagram of the dissimilar friction stir welding.

2. Literature Review

Muthu &jayabalan [1] studied that the aluminum and copper were carried out by varying the tool travel speed from50 mm/min to 90 mm/min. The joint properties were evaluated and characterized with respect to the stir zone formation, intermetallics formation and its distribution. Tool traverse speed of 70 mm/min and 80 mm/min resulted in the optimum range of heat input to form defect free stir zone. The reduced diffusion rate and time prevailing at tool traverse speed of 80 mm/min resulted in lower intermetallic thickness of 1.9 m. The continuous nano scaled thin intermetallic layers resulted in higher tensile strength and joint efficiency of 113 MPa and 70% respectively. Hyung et al. [2] investigated how the interfacial inter-metallics compounds were formed in the Al–Cu bonds. The study revealed that the thickness of the intermetallic compound layer is a function of temperature and holding time. The atomic diffusion of Cu and Al through the intermetallic compound is the main controlling process for the intermetallic compound growth. Mubiayi and Akinlabi [3] reviewed that the friction stir welding of dissimilar rmaterials focusing on aluminium and copper has been successfully conducted. Furthermore, new studies on FSW between aluminium and copper with respect to the process optimization and selection of cost effective FSW tools to produce sound welds still has to be developed. Thus, the use of the FSW technique to join aluminium and copper alloys and material shapes is of importance in the development of their industrial applications. Elatharasan and Senthil Kumar [4] has studied that central composite design technique and mathematical model was developed by response surface methodology with three parameters, three levels and 20 runs, was used to develop the relationship between the FSW parameters (traverse speed, rotational speed, axial force,) and the responses (tensile strength, Yield strength (YS) and %Elongation (%E) were established. They have concluded that UTS and YS of the FS welded joints increased with the increase of tool rotational speed, welding speed and tool axial force up to a maximum value, and then decreased. And also TE of joints increased with increase of rotational speed and axial force, but decreased by increasing of welding speed, continuously. Barekatain,et, al., [5] conducted friction stir welding between dissimilar metals AA 1050 aluminum alloy and commercially pure copper. The annealed and severely plastic deformed sheets were subjected to friction stir welding (FSW) at different rotation and welding speeds. They have kept Cu in advancing side. A range of welding parameters which can lead to acceptable welds with appropriate mechanical properties was found. For the FSW edCGPed samples, it was observed that the welding heat input caused grain growth and decrease in hardness value at Al side of the stir zone. Further investigations showed that several forms of intermetallic compounds were produced. M.H.Shojaeefard*et al.* [6] conducted research on Al–Mg and CuZn34 alloys were lap joined using friction stir welding during which the aluminum alloy sheet were placed on the CuZn34 and the process parameters were optimized using Taguchi L9 orthogonal design of experiments (DOE). The rotational speed, tool tilt angle and traverse speed were the parameters taken into consideration. The optimum levels of the rotational speed, tile angle and transverse speed are 1120 rpm, 1.5 and 6.5 mm/min respectively. In this investigation rotational speed plays a important role and contributes 40% to the overall contribution. In verification test, it can be observed that the deviation between the predicted value of the tensile shear force and the experimental value of that is found as 2.5%. Increasing the rotational speed of the tool at constant welding speeds entail increase of the tensile shear force to maximum, and then a decrease in tensile shear force occurred. Bisadi et al. [7] in friction stir lap welding of 2.5 mm-thick AA 5083 to 3 mm-thick commercially pure copper sheets. The authors observed channel-like defects near the sheets interface, for very low temperatures, and cavities at the interface of stirred aluminium particles and the copper, for high welding temperatures. According to the authors, high welding temperatures lead to higher aluminium diffusion to the copper sheet, which makes that aluminium particles are forced into the copper sheet and, after quenching, some cavities are formed at the interface of the particles and the copper matrix. Besides the high temperatures, the different melting temperatures and contraction coefficients of both materials are pointed by the authors as the main factors on the basis of this type of defect. It was also reported that, for the range of welds tested, the hardness values of the stirred aluminium alloy were considerably lower than that of the aluminium base material, contrary to the stirred copper hardness, which was in over-match relative to the base material. Elatharasan et al. [8] in their research study, experimental analysis of process parameters of friction stir welding and its optimization. They identified different process parameters like tool rotational speed, welding speed and axial force that have significant role in deciding joint characteristics on an aluminum alloy. They have adopted Response Surface Methodology (RSM) and ANOVA for the optimization of process parameters. The outcomes of the experimentation are ultimate tensile strength, yield strength increased with increase in tool rotational speed, welding speed and tool axial force. The percentage of total elongation increased with increase in rotational speeds and axial force but decreased when there is increase in welding speed continuously. The results documented as maximum tensile strength is 197.50MPa, yield strength is 175.25MPa, percentage of total elongation is 6.96 was exhibited by the friction stir welding joints fabricated with optimized parameters of 1199rpm rotational speed, 30mm/min welding speed and 9 KN axial force.

Koilraj et al., [9] in their work, optimization of process parameters of friction stir welding of dissimilar aluminum alloys (copper, aluminum and magnesium alloys) using Taguchi technique (Taguchi L16 orthogonal design of experiments), considered parameters rotational speed, traverse speed, tool geometry and ratio between tool and shoulder diameter and pin diameter for optimization to investigate tensile strength of the joint. The results were analyzed with the help of analysis of variance (ANOVA) and concluded that optimum levels of tool rotational speed is 700 rpm , traverse speed is 15mm/min , ratio between tool shoulder diameter and pin diameter is 3, pin tool profile is cylindrical threaded and finally friction stir welding produces satisfactory butt welds. Yahya Bozkurt [10] has done work on optimization of friction stir welding process parameters to achieve maximum tensile strength in the polyethylene slab. Three process parameters, tool rotational speeds, tool traverse speed, and tilt angle of the tool were identified for optimization. The material taken for study is high density polyethylene sheet which is a thermoplastic to determine welding process parameters on ultimate tensile strength of the weld for good joint efficiency. LI Xia-wei, et al. [11] The dissimilar friction stir welding of pure copper/1350 aluminum alloy sheet with a thickness of 3 mm was investigated. Most of the rotating pin was inserted into the aluminum alloy side through a pin-off technique, and sound welds were obtained at a rotation speed of 1000 r/min and a welding speed of 80 mm/min. Complicated microstructure was formed in the nugget, in which vortex-like pattern and lamella structure could be found. No intermetallic compounds were found in the nugget.

Lakshminarayanan and Balasubramanian [12] evaluated the percentage of the contribution of the different FSW process parameters. The survey concluded that the tool travel speed contribution was 33% towards the tensile force of the FSW joints. Liu et al. [13] observed that fusion welding also creates solidification defects like porosity, hot cracking, etc. Many researchers have concluded that Friction Stir Welding (FSW) can overcome the problems that occur during the fusion welding process. It was also concluded that FSW is a potential candidate capable of joining dissimilar materials which are highly incompatible. Since FSW puts together material sat solid state, many metallurgical reactions above the melting temperature can be avoided. FSW was previously introduced tojoin the dissimilar combinations like Al to Mg. Won et al. [14] studied the effect of the intermetallic com-pounds on the mechanical properties of the friction welded Al–Cu joints. Their investigation concluded that the thickness of the inter-metallic compound layer increases as the annealing time increases. A higher intermetallic thickness of 105 m is formed at the highest temperature and the longest dwell time. As the tool travel speed increases, the intermetallic thickness is reduced. This is due to the low thermal activation energy for the diffusion of atoms, lower fraction of Cu in the stir zone and absence of lamellar patterns of Al–Cu materials in the stir zone. The interfacial reaction between these two incompatible mate-rials formed phases like Al-Cu, Al2Cu and Al4Cu9in the stir zone.

3. Experimentation Work

To achieve the foremost objective of the present investigation, the tentative work is conduct in the following sequence given below:

- Manufacturing of friction stir welding tool with the threaded cylindrical pin using H13 tool steel.
- Fabrication of friction stir butt welds of AA6061 under the effect of different input process parameters.
- Investigation of the response process characteristics such as; Ultimate tensile strength (UTS), and micro-hardness of the prepared weld.

Figure 2: Base Plates of work material: AA6061

The detailed investigational procedures involved in each stage of the experimental work are briefed in the following sections.The base metal used in this investigation is AA6061 as shown in the Fig 2. The chemical composition of the base metals AA6061 as provided by the supplier (Fabri-Tech Materials Ltd., Meerut, India) is given in Table 1. The mechanical properties of the base metals is also evaluated and it is given in Table

Table 1 Chemical Composition of the work plate: AA6061

Alloy AA6061	**Zn**	**Mg**	**Si**	**Fe**	**Cr**	**Mn**	**Cu**	**Ti**	**Al**
Content (%)	0.8-1.2	0.88-1.02	0.67 max	0.45 max	0.14-0.26	0.02-0.06	0.32 max	0.1 max	Remainder

Table 2 Mechanical properties of the work plate AA6061

Tensile strength (MPa)	**Elastic Modulus (GPa)**	**% Elongation**	**Density (g/cc)**	**Hardness (HB500)**
115	70-80	23	2.7	30

Single pass butt welds are produced in 6 mm thick plates of AA6061 using indigenously designed friction stir welding machine. The photograph of the Friction Stir Welding machine is given in Figure 3. The machine can rotate the tool up to 2000 rpm, apply an axial load of up to 40 KN and the transverse speed can be 400 mm/min.

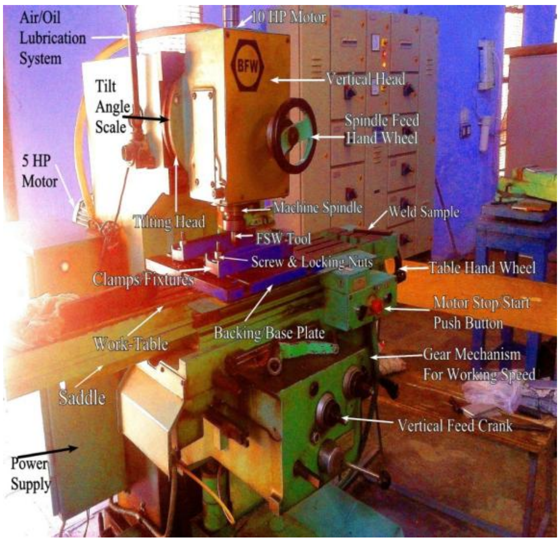


Figure 3: Friction Stir Welding Machine Set-up

A cylindrical taper column tool without square head (H13 tool steel) with shoulder diameter 18 mm, pin length 6 mm and pin diameter 5.9 mm used for the current work. The cavity angle of tool is 6°. Plate dimensions (100 mm × 50 mm) cut by using power hacksaw. All Fabricated joints of AA6061as shown in Fig 4. The mechanical clamps are used to clamp the plate on the worktable of the machine. The butt joints were fabricated normal to the rolling direction.

Figure 5 Fabricated Plate of AA6061

The details regarding welding parameters used in this study are given in Tables 2

Table 2. FSW Parameters and their levels

SYMBOL	**WELDING PARAMETER**	**UNIT**	**LEVEL 1**	**LEVEL 2**	**LEVEL 3**
A	ROTATIONAL SPEED	RPM	600	800	1000
B	WELDING SPEED	MM/MIN	10	20	30
C	TOOL TILT ANGLE	DEGREE	1	2	3

The American Society for Testing and Materials (ASTM-E8) guidelines are followed for preparing the tensile test specimens. The power hacksaw is used to cut the smooth profile of tensile. The experiments are conducted according to the designed L9 Orthogonal Array and the values of ultimate tensile strength and micro hardness testing results are listed in Table 3.

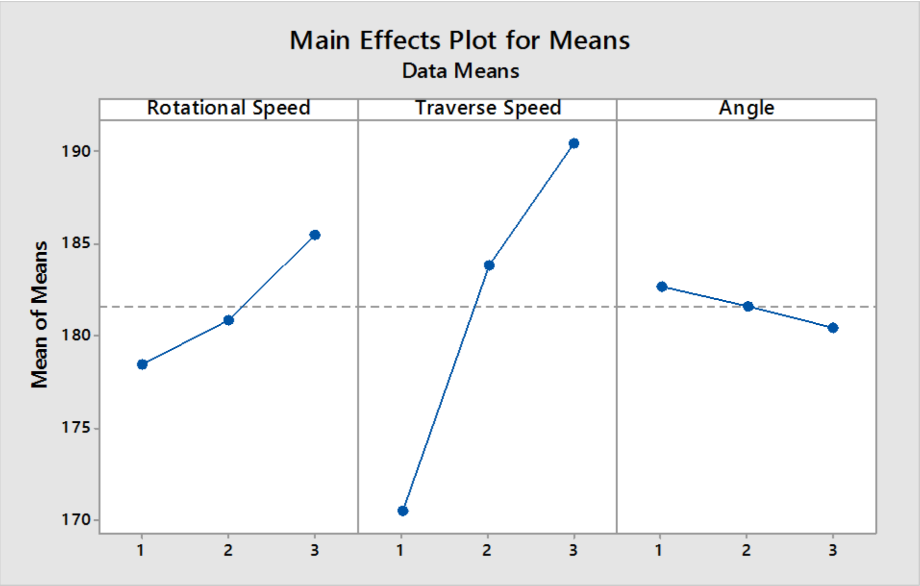
Table 3 Experimental Layout Using L9 Orthogonal Array for Tensile Strength (UTS) & Micro hardness.

Std.	Run	Block	Rotating Speed (rpm)	Welding Speed (mm/min)	Tilt Angle (degree)	UTS (MPa)	Micro-hardness (Hv)
5	1	Block 1	600	10	1	169.60	52.10
6	2	Block 1	600	20	2	179.65	51.95
3	3	Block 1	600	30	3	186.10	56.55
4	4	Block 1	800	10	2	169.65	53.10
9	5	Block 1	800	20	3	183.10	54.00
1	6	Block 1	800	30	1	189.75	57.05
2	7	Block 1	1000	10	3	172.20	56.15
7	8	Block 1	1000	20	1	188.75	64.05
8	9	Block 1	1000	30	2	195.65	68.80

4. Results and Discussions

After conducting the experiment with different setting of the input parameters, the experimental values of the considered output variables were recorded and plotted as per taguchi's DOE methodology [14-16]. The analysis of the result obtained has been performed according to the standard procedure recommended by Taguchi. The objective function is targeted to maximize the ultimate tensile strength, and micro-hardness of the conducted FSW joints. The optimum levels of the process parameters are assessed and confirmed by conducting the confirmatory test runs. The effect of FSW process parameters such as; tool rotational speed, welding speed, and tool tilt angle on ultimate tensile strength, and micro-hardness are elaborated and discussed. For ultimate tensile strength (UTS), higher-the-better S/N ratio was applied for the transforming the raw data corresponding to the different experimental run. In similar fashion, for micro-hardness, larger-the-better S/N ratio was applied for the transforming the raw data corresponding to the different experimental run.

The main effect can be studied by the level average response analysis of the mean data and S/N ratio. The analysis is done by averaging the mean and/or S/N data at each level of each parameter and plotting the value in graph. The level average response from the mean data helps in analyzing the trend of performance characteristics with respect to variation of the factor under study.For investigated ultimate tensile strength (UTS), and micro hardness (MH), the main effect of raw data and those of S/N ratio for response variable has been shown in figure 6 and figure 7, respectively.



Optimum Combination: A3B3C2 (TRS=1000 rpm, WS = 30 mm/min, TTA=1 degree)

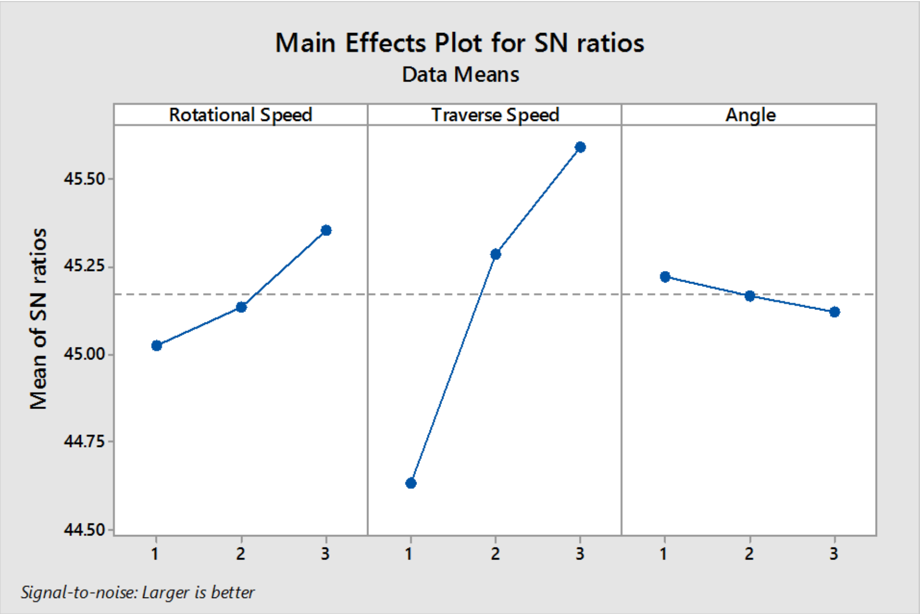
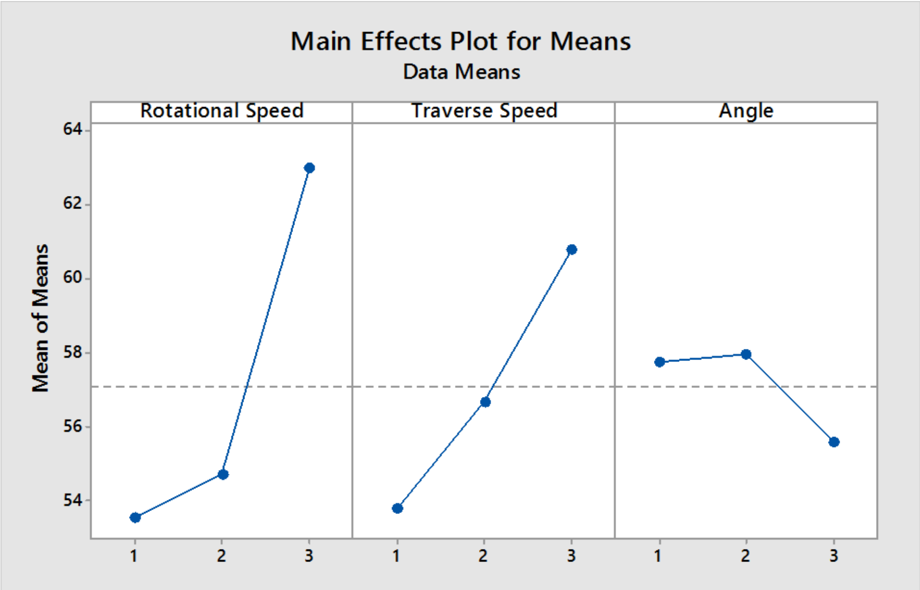


Figure 6Effect of Process Parameters on UTS – Raw Data and S/N Ratios



Optimum Combination: A3B3C2 (TRS=1000 rpm, WS = 30 mm/min, TTA=2 degree)

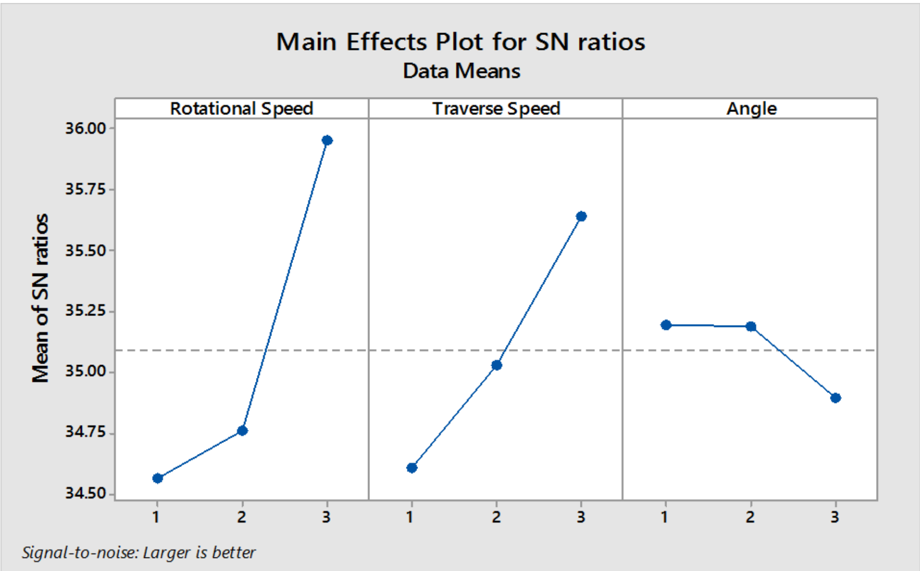


Figure 7Effect of Process Parameters on Micro-hardness – Raw Data and S/N Ratios

ANOVA is well known as – "statistical method" used to interpret experimental data and make the necessary decision. ANOVA is a statistical based decision tool for detecting any difference in the average performance of group of item tested. ANOVA (general linear model) for mean value has been performed to identify the significant parameters to quantify their effect on the performance characteristics. ANOVA test for the obtained experimental data is given in the tables 4 to 5.

Table 4ANOVA Table for Response R1 (Ultimate Tensile Strength)

Source	**DOF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	
Tool Rotational Speed	2	3135.71	1567.85	456.74	0.000	*
Welding Speed	2	121.53	60.76	17.70	0.000	*
Tool Tilt Angle	2	14.77	7.39	2.15	0.163	**
Error	11	37.76	3.43			
Lack-of-Fit	2	37.17	18.59	285.96	0.000	
Pure Error	9	0.59	0.07			
Total	17	3309.77				
Model Summary						
S	**R-sq**	**R-sq (adj)**	**R-sq (pred)**			
1.85275	98.86%	98.24%	96.95%			
***** denotes significant terms, and ****** reflects the insignificant terms.						

Final Model Equation in Terms of Coded Factors (*for UTS*):

UTS = 84.994 - 13.828 A1 - 3.944 A2 + 17.772 A3 - 2.778 B1 - 0.694 B2 + 3.472 B3

- 0.061 C1 + 1.139 C2 - 1.078 C3

Table 5. ANOVA Table for Response R2 (Micro-hardness)

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	
Tool Rotational Speed	2	1318.53	659.265	3313.90	0.000	*
Welding Speed	2	52.22	26.112	131.25	0.000	*
Tool Tilt Angle	2	0.16	0.082	0.41	0.673	**
Error	11	2.19	0.199			
Lack-of-Fit	2	0.20	0.102	0.46	0.645	
Pure Error	9	1.98	0.221			
Total	17	1373.10				
Model Summary						
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**			
0.446026	99.84%	99.75%	99.57%			
***** denotes significant terms, and ****** reflects the insignificant terms.						

Final Model Equation in Terms of Coded Factors (*for MH*):

$$\text{Micro Hardness} = 159.517 - 10.250\,A1 - 0.450\,A2 + 10.700\,A3 - 1.633\,B1 - 0.717\,B2 + 2.350\,B3 + 0.000\,C1 + 0.117\,C2 - 0.117\,C3$$

For UTS, the predicted response value proposed by the analytical model is ***202.378 MPa.*** *For* ***Micro-hardness****, the predicted response value proposed by the analytical model is* ***67.58 Hv.***

After performing the confirmation experimental runs at the optimum setting, ultimate tensile strength,

4.1 Effect of Tool Rotational Speed (TRS)

The results of present method clearly indicate that the rotational speed of 1000 rpm yields a maximum tensile strength and micro hardness when compared to 600 and 800 rpm. When the rotational speed is at 600 rpm, the ultimate tensile strength of the FSW joints of AA6061 has been revealed as low. This is due to the insufficient heat input, which results in a lack of stirring. At high speed, the excessive materials are thrown to the upper surface of the base plate, and micro-hardness is again revealed as best at tool rotation of 1000 rpm and low at 600 rpm. The ANOVA test results showed that the A3B3C1 is the optimum parameters setting for the ultimate tensile strength (UTS) for which tool rotation speed is 1000 rpm, welding speed is 30 mm/min, and tool tilt angle is 2 degrees, while performing friction stir welding of AA6061 work sample.

4.2 Effect of Welding Speed

Three levels of welding speed are taken into consideration for this investigation. There are 10 mm/min, 20 mm/min, and 30 mm/min. When the welding speed is at the level of 30 mm/min, the ultimate tensile strength, and micro-hardness of the FSW joint is superior through the utilization of Taguchi method of optimization. The ultimate tensile strength of the FSW joints enhances with increase in welding speed. The ANOVA test results showed that the A3B3C2 is the optimum parameters setting for the micro-hardness (MH) for which tool rotation speed is 1000 rpm, welding speed is 30 mm/min, and tool tilt angle is 2 degrees, while performing friction stir welding of AA6061 work sample.

4.3 Effect of Tool Tilt Angle

Three levels of tool tilt angle have been taken into consideration for this experimental investigation. They are 1, 2, and 3 degrees. As the tilt angle of the tool increases, the friction force on the leading edge decreases. The temperature at trailing edge is higher due to which plastic deformation and mixing of materials are uniform. But at higher tool tilt angle pin material fill up is not done properly by tool shoulder and weak welding joint is made. In this way tool tilt angle affects the welding temperature as well as strength of the joint. Irrespective of the methods Taguchi, the superior ultimate tensile strength, and micro-hardness of the FSW joints is reported when the tool tilt angle is set at 2 degrees. The effect of tool tilt angle on the ultimate tensile strength as well as on micro-hardness of FSW joints has been revealed as- "*not significant*".

5. Conclusion

The friction stir welding of AA6061 has been conducted in the present experimental work. The following conclusions can be drawn:

- ANOVA results for Ultimate tensile strength (UTS) shows that the F-value for the considered input process parameters namely; tool rotational speed, welding speed, and tool tilt angle are 456.74, 17.70, AND 2.15, respectively. Out of these three studied variables, tool rotational speed, and welding speed have been attained as the significant terms at 95% confidence level.
- ANOVA results for Micro-hardness shows that the F-value for the considered input process parameters namely; tool rotational speed, welding speed, and tool tilt angle are 3313.90, 131.25, and 0.41, respectively. Out of these three studied variables, tool rotational speed, and welding speed have been attained as the significant terms at 95%

confidence level, whereas tool tilt angle has been revealed as insignificant process parameters.

The current research work examines the process parameter optimization and characterization of Friction stir welding of AA6061. The process responses that have been considered for optimization are Ultimate tensile strength (UTS), and the Micro-hardness (MH) of the FSW welded joint. The significant process parameters have been identified as well as the optimum levels of the process parameters were attained out. After performing the confirmation experimental runs at the optimum setting, ultimate tensile strength, and micro-hardness have been observed as; 110.21 MPa, and 175.86 Hv, respectively. These experimental values are very close enough to the predicted values suggested by the developed mathematical model.

References

[1] Muthu, M. F. X., &Jayabalan, V. (2015). Tool travel speed effects on the microstructure of friction stir welded aluminum–copper joints. *Journal of Materials Processing Technology*, *217*, 105-113.

[2] Cho, J. H., Kim, W. J., & Lee, C. G. (2014). Texture and microstructure evolution and mechanical properties during friction stir welding of extruded aluminum billets. *Materials Science and Engineering: A*, *597*, 314-323.

[3] Mubiayi, M. P., &Akinlabi, E. T. (2013, April). Friction stir welding of dissimilar materials: an overview. In *Proceedings of World Academy of Science, Engineering and Technology* (No. 76, p. 633). World Academy of Science, Engineering and Technology (WASET).

[4] Elatharasan, G., & Kumar, V. S. (2013). An experimental analysis and optimization of process parameter on friction stir welding of AA 6061-T6 aluminum alloy using RSM. *Procedia Engineering*, *64*, 1227-1234.

[5] Barekatain, H., Kazeminezhad, M., &Kokabi, A. H. (2014). Microstructure and mechanical properties in dissimilar butt friction stir welding of severely plastic deformed aluminum AA 1050 and commercially pure copper sheets. *Journal of Materials Science & Technology*, *30*(8), 826-834.

[6] Shojaeefard, M. H., Behnagh, R. A., Akbari, M., Givi, M. K. B., &Farhani, F. (2013). Modelling and Pareto optimization of mechanical properties of friction stir welded AA7075/AA5083 butt joints using neural network and particle swarm algorithm. *Materials & Design*, *44*, 190-198.

[7] Bisadi, H., Tavakoli, A., Sangsaraki, M. T., &Sangsaraki, K. T. (2013). The influences of rotational and welding speeds on microstructures and mechanical properties of friction stir welded Al5083 and commercially pure copper sheets lap joints. *Materials & Design*, *43*, 80-88.

[8] Elatharasan, G., & Kumar, V. S. (2013). An experimental analysis and optimization of process parameter on friction stir welding of AA 6061-T6 aluminum alloy using RSM. *Procedia Engineering*, *64*, 1227-1234.

[9] Koilraj, M., Sundareswaran, V., Vijayan, S., & Rao, S. K. (2012). Friction stir welding of dissimilar aluminum alloys AA2219 to AA5083–Optimization of process parameters using Taguchi technique. *Materials & Design*, *42*, 1-7.

[10] Bozkurt, Y. (2012). The optimization of friction stir welding process parameters to achieve maximum tensile strength in polyethylene sheets. *Materials & Design*, *35*, 440-445.

[11] Li, X. W., Zhang, D. T., Cheng, Q. I. U., & Zhang, W. (2012). Microstructure and mechanical properties of dissimilar pure copper/1350 aluminum alloy butt joints by friction stir welding. *Transactions of Nonferrous Metals Society of China*, *22*(6), 1298-1306.

[12] Lakshminarayanan, A. K., &Balasubramanian, V. (2008). Process parameters optimization for friction stir welding of RDE-40 aluminium alloy using Taguchi technique. *Transactions of Nonferrous Metals Society of China*, *18*(3), 548-554.

[13] Ren, S. R., Ma, Z. Y., & Chen, L. Q. (2007). Effect of welding parameters on tensile properties and fracture behavior of friction stir welded Al–Mg–Si alloy. *Scripta Materialia*, *56*(1), 69-72.

[14] Lee, W. B., Bang, K. S., & Jung, S. B. (2005). Effects of intermetallic compound on the electrical and mechanical properties of friction welded Cu/Al bimetallic joints during annealing. *Journal of Alloys and Compounds*, *390*(1-2), 212-219.

[15] Singh, Ravi Pratap, Ravinder Kataria, Jatinder Kumar, and JagesvarVerma. "Multi-response optimization of machining characteristics in ultrasonic machining of WC-Co composite through Taguchi method and grey-fuzzy logic." *AIMS MATERIALS SCIENCE* 5, no. 1 (2018): 75-92.

[16] Kataria, Ravinder, Jatinder Kumar, and B. S. Pabla. "Experimental investigation into the hole quality in ultrasonic machining of WC-Co composite." *Materials and Manufacturing Processes* 30, no. 7 (2015): 921-933.

[17] Singh, Ravi Pratap, Jatinder Kumar, Ravinder Kataria, and Sandeep Singhal. "Investigation of the machinability of commercially pure titanium in ultrasonic machining using graph theory and matrix method." *Journal of Engineering Research* 3, no. 4 (2015).