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FSW of AA-6061-T6 Aluminum Alloys: ANNOVA Analysis and Mechanical Testing

Kanishka Jha[1], Ravinder Kataria[2]
[1]Associate Professor, School of Mechanical Engg., Lovely Professional University
[2]Assistant Professor, School of Mechanical Engg., Lovely Professional University
Corresponding Author: kataria.ravinder07@gmail.com

ABSTRACT

Friction stir welding is a relatively new &one of the most significant solid-state welding technology used for welding similar and dissimilar materials without fusion or filler content. The process is globally accepted due to output sensitivity in terms ofexposure to elevated temperature, sound welds and comprehensive plastic deformation.FSW has inspired researchers and one of the most advanced topics for joining dissimilar materials. This article presents the Friction Stir set-up for welding (FSW) of AA6061-T6was used for conducting experiments and to further enhancing its mechanical properties. From the analysis of S/N ratio, it has been revealed that at a welding speed, tool rotational speed and tilt angle of tool of: 950 rev/min, 20 mm/min, and 3 degrees, respectively, the maximum ultimate tensile strength and for maximum attainment of studied micro-hardness, the parameter’s setting is as; tool rotational speed as 950 rev/min, welding run speed as 20mm/min, and tilt angle for tool as 2 degree. Optimized parameters values have also been attained to provide the studied process responses at their better levels.

Keywords: Alloys, Friction Stir Welding, Joining, ANNOVA.

Introduction

Friction stir welding (FSW) is an innovative green solid-state joining technique in which agglomerate takes place at temperatures lower than the melting point of the similar or dissimilar metals being joined and without use of a brazing filler metal with no harmful emissions [1]. 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. Due to the enormous differences in mechanical and metallurgical

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properties of Al–Cu dissimilar joints the fabrication is very difficult by fusion welding process,because the Al was easily oxidized at elevates temperature and some welding cracks created in a weld joint [2-5].

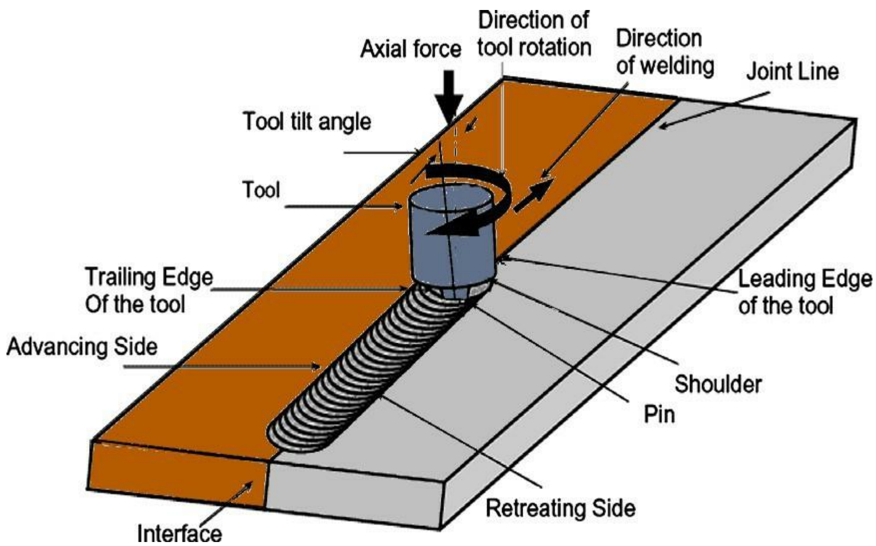

Figure 1: Schematic diagram of the dissimilar friction stir welding.

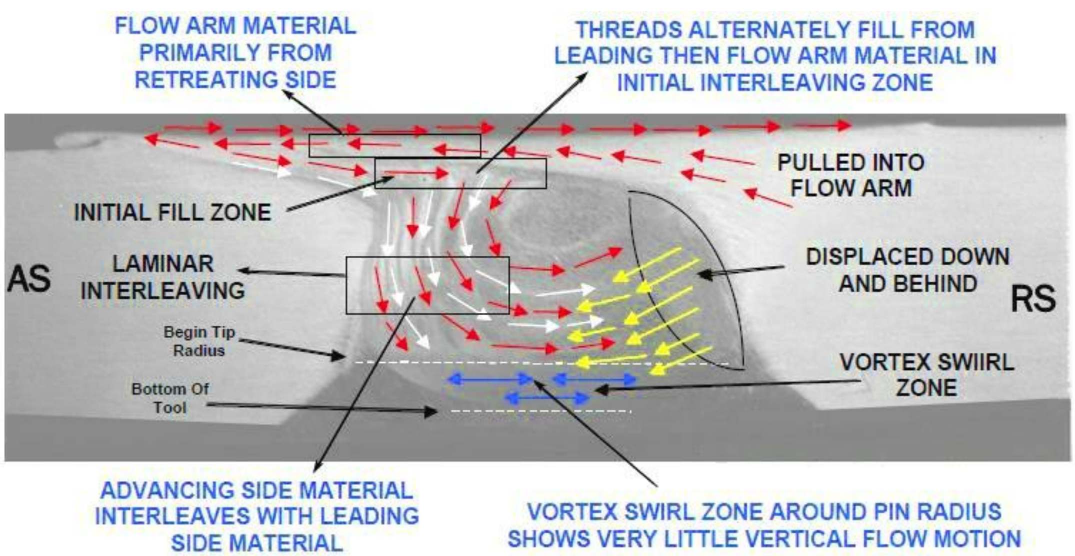

Figure 2: Material Flow Process

The detailed description about the carried research investigations by past researchers in the broad field of friction stir welding, its thorough applications in vast ranged industries, attempt of

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taguchi philosophy with FSW, process behavior under the effect of variable parameter environment, etc. has been reported out. It mainly focuses on the effect of Friction Stir Welding process parameters on the ultimate tensile strength (UTS), and micro-hardness of the weld along with the usage of single objective optimization tools employed throughout for the said process.Goyal et al. [6]optimized the friction stir welding using RSM technique and carried out their research on AA3003 aluminium alloy to maximize the ultimate tensile strength (UTS) of the welded joint. Process influential parameters are RPM of tool, tool tilt angleand welding speed. Analysis of variance (ANOVA) being analyzed and response surface graph also plotted to examine the parameters and the value of tensile strength is found 127.22 MPa at tool rotational speed 977.7, welding speed 74.64 mm/min and tool tilt angle 1.52 degree. Goyal et al. [7] discussed the effects of tool pin profile of friction stir welding and their effect on friction stir welding (FSW). Five different pin profiled tool has been taken to perform the welding to observe the best profile of the tool to produced sound quality of weld. AA5083 H32 and AA6061-T6 T6 aluminium alloys sheets of thickness 5mm used to performed welding. Kundu et al. [8] studied merits of friction stir welding over other joining process. There is no solution required to join the pieces, defect free welding, superior mechanical characteristics and eco-friendly process. The main advantage of the process dissimilar alloys can be welded easily. Rjeesh et al. [9] studied the process parameters using Taguchi technique of AA2014-T56. Analysis of variance (ANNOVA) is studied and found that the transverse speed influences the tensile strength and most significant values are found at 355rpm tool rotation speed, 31.5mm/min welding speed and 2-degree tool tilt angle. Caken et al. [10] worked on AA7075-T6 aluminum alloy and pure copper (Cu). The study was focused on the temperature distribution of the plates by taking different process parameters and constant welding speed i.e. 32mm/min and observed that the heat is directly proportional to number of tool revolution but up to a certain limit. Rane and Yadav [11]applied the friction stir welding (FSW) on aluminumaluminum (Al-Al), copper-copper (Cu-Cu) and aluminum- copper (Al-Cu) to study the effects of tool rotation speed, welding speed on hardness and tensile strength. Butt joint welding is carried out focusing on Al-Cu offset during welding operation and maximum tensile strength obtain at tool rotation speed 800 rpm, welding run speed 60mm/min and proper offset in tool of 2mm. The following gaps have been identified from the conducted literature work:

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- Very limited amount of research work has been carried out so far on the friction stir welding of AA6061-T6.
- Most of the investigations have been targeted to study the influence of an inadequate number of process parameters on the micro-hardness of welded joint.
- Very few researchers have been attempted upon the study of maximum tensile strength in FSW of AA6061-T6.

Therefore, on the basis of above said observed gaps of literature, it was planned to investigate the influence of FSW several parameters on the ultimate tensile strength and micro-hardness in friction stir welding of an aluminium alloy (AA6061-T6) through taguchi's experimental design methodology.

Material and Methods

Among aluminum alloys, the series of 6xxxalloys are used in many areas like heat-treatable material, weldable aluminum alloy. In the current work copper and aluminium materials are important &extensively used in different engineering structure because to its distinctive performances like higherthermal conductivities, higherelectric conductivities, mechanical properties and having corrosion resistantnature.The chemical composition of the base metals AA6061-T6 as provided by the supplier (Fabri-Tech Materials Ltd., Meerut, India) is illustrated in Table 1 and mechanical of the base metals are also evaluated and represented in Table 2.

Table 1: Work piece Chemical Composition: AA6061-T6

AA6061-T6	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-T6

Tensile strength (MPa)	Elastic Modulus (GPa)	% Elongation	Density (g/cc)	Hardness (HB500)
276 MPa	70-80	12	2.7	50

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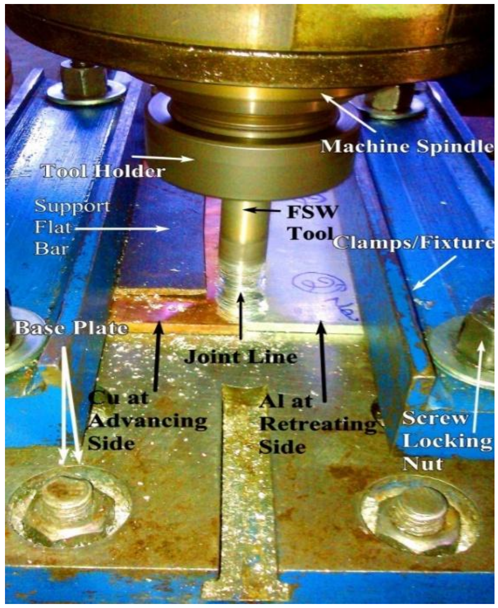

Figure 3: Friction Stir Set-up for Welding

The heat caused by high friction between the work piece and the tool that having forging actionand 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 [12-14].A cylindrical taper column tool without square head made up of H13 tool steel with shoulderdiameter 18mm, pin diameter 5.9 mm pin diameter 5.9mm pin length 6mm and used for the current work. The cavity angle oftool is 6°.Plate dimensions (100 mm × 50 mm) cut by using power hacksaw. The mechanical fixtures are used to hold the base plate on the worktable.

Table 3: Friction Stir Set-upInput Parameters and their respective levels for consideration

	LEVEL 1	LEVEL 2	LEVEL 3	SYMBOL
Rtational Speed(rpm)	550	750	950	A
Welding run speed(mm/min)	10	15	20	B
Tilt Angle for Tool(degree)	1	2	3	C

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Result and Discussion

Conduction of project with various input parameters was done and the experimental data set of the considered response variables were obtained and graphs were drawn as per taguchi'sDOE methodology. This chapter discusses the results obtained after conducting the dually replicated experimental runs, and also the optimized FSW's process parameter through utilizing Taguchi experimental design methodology. 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 [15-18].

Table 4: Experimental Designof 3 Input with L9 Orthogonal Array for Tensile Strength (UTS) & Micro hardness.

Run	**Rotating Speed(rpm)**	**Welding Speed (mm/min)**	**Tilt Angle (degree)**	**UTS (MPa)**	**Micro-hardness (Hv)**
1	550	10	1	169.60	52.10
2	550	15	2	179.65	51.95
3	550	20	3	186.10	56.55
4	750	10	2	169.65	53.10
5	750	15	3	183.10	54.00
6	750	20	1	189.75	57.05
7	950	10	3	172.20	56.15
8	950	15	1	188.75	64.05
9	950	20	2	195.65	68.80

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.For investigated tensile strength, and micro-hardness (MH), main effect of raw data for response variable has been shown in figure 4 and figure 5, respectively [19-22].

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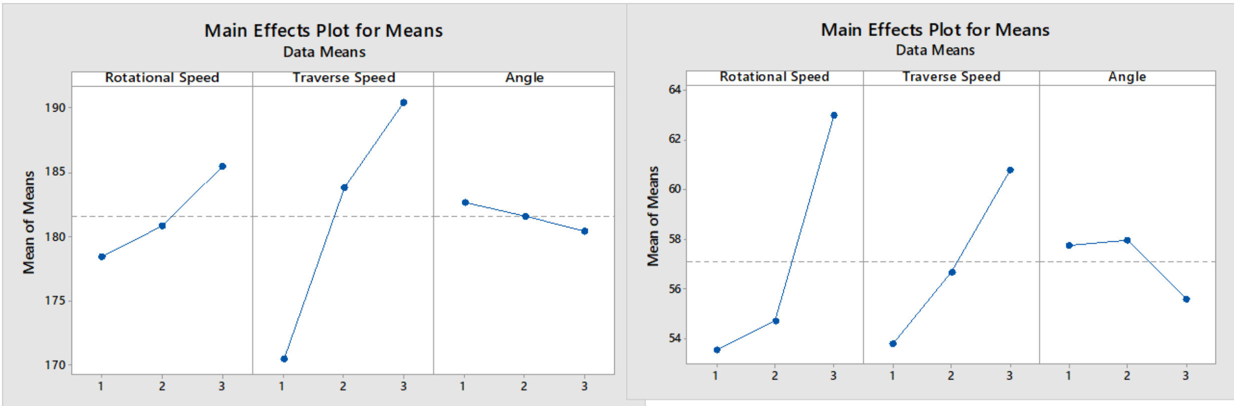

(a) (b)

Figure 4: (a) Main Effect Plots Showing OptimumCombination:A3B3C2 (RS=1000 rpm, WS = 30 mm/min, TA=1 degree), **(b)**Main Effect Plots Showing Optimum Combination:A3B3C2 (RS=1000rpm, WS = 30mm/min, TA=2-degree)

ANOVA test for the obtained experimental data is given in the tables 5 to 6.

Table 5:ANOVA Table for Response R1

Source	**DOF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Rotational Speed	2	3135.71	1567.85	456.74	0.000*
Welding Run Speed	2	121.53	60.76	17.70	0.000*
Tilt of Angle Tool	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.

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Table 6:ANOVA Table for Response R2

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.

The results of present method clearly indicate that the rotational speed of 950 rpm yields a maximum tensile strength and micro hardness when compared to 550 and 750 rpm. When the rotational speed is at 750 rpm, the ultimate tensile strength of the FSW joints of AA6061-T6 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 950 rpm and low at 550 rpm. The ANOVA test results showed that the A3B3C1 is the optimum parameters setting for the ultimate tensile strength (UTS) for which tool welding speed is 30 mm/min,rotation speed is 950 rpm, and tilt angle of tool is 2 degrees, while performing welding with friction stir of AA6061-T6 work sample.

Three levels of welding speed are taken into consideration for this investigation. There are 10, 15, and20 mm/min. When the welding run speed is of 20mm/min, the tensile strength and microhardness of 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.

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Three levels of tool tilt angle have been taken into consideration for this experimental investigation. They are 1, 2, and 3 degrees. With the increment in tilt angle, the friction force associated with the leading edge decreases significantly. This friction increases the temperature at trailing edge and uniform mixing of material and plastic deformation is ensured.For 3-degree tilt angle of tool weak welding joint is obtained due to improper filling of pin material by tool shoulder. Irrespective of the methods Taguchi, the superior micro-hardness and ultimate tensile strength of the FSW joints is reported when the tool tilt angle is set at 2 degrees.

CONCLUSION

The welding with friction stir process of AA6061-T6was taken for analysis in thisstudy. 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 run speed, and tilt angle of tool are 456.74, 17.70, AND 2.15, respectively. Out of these three studied variables, all parameters 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 run speed, and tilt angle of tool 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-T6. 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-hardnesshave 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.

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