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Optimization of Welding Parameters for Friction Stir Lap Welding of AA6061-T6 Alloy

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Abstract

Friction Stir Welding (FSW) is currently used in many aircraft and aerospace sheet metal structures involving lap joints and there has been growing interest in recent years in utilizing this process for joining aluminum alloys. In this paper, Friction Stir Lap Welding (FSLW) of the 6061-T6 aluminum alloy was carried out to obtain the optimum welding condition for maximum shear strength where the rotational speed, axial load, and welding speed were taken as process parameters. An L-9 orthogonal array, a Taguchi Method with consideration of three levels and three factors was designed and executed for conducting trials. Analysis of variance (ANOVA) and Signal to Noise (S/N) ratio were employed to investigate the influence of different welding parameters on the shear strength and obtain the optimum parameters. The Fisher-Test was also implemented to find the design parameter which had the most important effect on the characteristic of quality. The results indicated that the tool rotational speed had the maximum percentage contribution (51%) on the response (shear strength) followed by the welding speed (38%) and the axial load (8%) while the percentage of error was 3%. However, to confirm the main effects for the means and S/N ratios of the experiment, theoretical shear strength values were computed to predict the tensile strength. The maximum shear strength of 60 MPa was achieved and the effectiveness of the method was confirmed. The optimum parameter combinations that provided higher shear strength were: rotational speed of 1200 rpm, welding speed of 45 mm/min and the axial load of 11.5 kN.

Keywords

Friction Stir Welding, Lap Joint, AA6061 Alloy and Optimization

1. Introduction

Friction Stir Welding (FSW) is a new and a very effective solid-state joining technique invented in TWI in Cambridge, England in 1991 for joining aluminum alloys [1]. The welding process majorly encompasses a non-dispensable rotating tool with a design comprising a pin and a shoulder that travels along the longitudinal length of the weld seam and join the work pieces [2]. The properties of the welded metal zone usually have low distortion because of lower welding temperature and higher joint strength when compared to the welded metals from conventional welding methods. Hence, this method eliminates the need for gas shielding requirement and joint edge preparations before welding application. Over the years and after decades of research, the technique has proved to be a versatile method in the academia which is energy efficient, environment-friendly and avoids the formation of solidification, cracking and porosity.

Aluminum Alloy 6061-T6 is widely utilized in the construction of aerospace structures, such as wings and fuselages in commercial aircrafts, several parts of a remote-controlled model aircraft and helicopter rotor components. AA6061-T6 has also its wide applications in the automotive industry such as parts like chassis and engine parts. In these past few years in these industries, there is an ongoing effort to reduce the weight of aluminum alloy in assemblies of parts which use conventional methods of welding with filler materials. FSW is presently able to weld several aluminum alloys from various ranges of series bolstering the fact that it was contemplated to be non-weld able alloys due to a vast decrease in the strength of the joint in contrast with the base metal. Several researchers have tried to explore this field of industry requirement. Liu *et al.* [3] joined AA6061-T6 alloy using FSW in butt configuration where the hardness value and the grain size decreased in the weld zone when compared to the base metal. Rathinasuriyan *et al.* [4] carried out FSW in submerged condition and identified the defect-free samples using radiography technique. Sankar *et al.* [5] have studied the mechanical properties on AZ31B Mg alloy by FSP in air, under water and under liquid nitrogen.

Various riveted joints in aircraft structures have mostly been substituted by friction stir welded lap joints where one must understand that riveted joints were the major method of joining aerospace structures since its manufacturing began [6]. Rivet holes are notoriously known for probable junctures of crack and corrosion propagation. Resistance spot welding (RSW) is also a major choice in welding for various economic reasons such as the omission of fasteners that point considerable weight and cost savings [7]. However, Dubourg *et al.* [8] investigated the lap joints of aluminum alloys of AA2024-T3 and AA7075-T6 using FSW where the welded joint is stronger than the comparable riveted or resistance spot welded lap joints for the major aluminium alloys. Al-Si and Mg-Al-Zn alloys were lap joined using friction stir welding by Chen and Nakata [9] where the stirring pin is plunged into the lower metal to produce a bonding mechanism of mechanical mixing that enhances bonding strength and the lower welding speed avoids cracks and improves the joint strength. Later on, Cao *et al.* [10] made lap joints on AZ31B-H24 magnesium alloy and A2198-T4 aluminum alloy using an FSW process where the fracture occurred at the heat affected zone of the base metal. They have achieved the highest bonding strength close to the base metal while lap joining 1060 aluminium alloy and commercially pure copper [11] [12].

The predominant problems that aerospace and automotive industries generally face in metal welding processes are poor weld quality and strength of the weld. This is due to improper selection of parameters which have a significant influence on the strength of the weld that affects the quality and the strength of the bond formation. Ashok Kumar *et al.* [13] considered axial load as one of the process parameters while optimizing the parameters for maximum tensile strength. Lokesh *et al.* [14] optimized the process parameters for SFSW using the Taguchi technique in order to get maximum hardness. Rathinasuriyan *et al.* [15] developed a mathematical model to optimize the parameters using response surface methodology while conducting submerged FSW process.

From the viewpoint of application in the industry after much study, it would be more significant to optimize parameters of the Friction Stir Lap Welding (FSLW) for maximum mechanical properties of the joints. However, due to limited work on this area. In this study shows the optimization of process parameters such as rotational speed (rpm), axial load (kN) and welding speed (mm/min) for friction stir lap welding (FSLW) of 6061-T6 aluminium alloy.

2. Experimental and Testing Details

2.1. Experimental Setup

The base metal (BM) used for the experiment is commercially available AA6061-T6 alloy which is 300 mm in length, 300 mm in width and 3 mm in thickness. The chemical compositions and mechanical properties are listed in **Table 1** and **Table 2**.

A cylindrical tool with 18 mm shoulder diameter, 6 mm pin diameter and 5 mm pin length, made up of H13 tool steel is used. The tool used is shown in **Figure 1**.

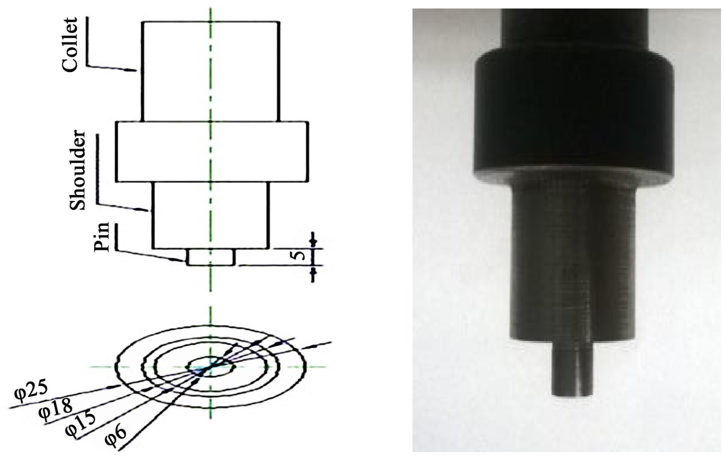
To make a lap joint, the work pieces were lapped together and clamped on the backing plate of FSW machine and the rotating tool was brought in contact with the top surface of work pieces. The tool was made to travel along the length of the junction where the two sheets met where a metallic bond was formed. The

Table 1. Chemical composition of AA6061-T6 (in weight %).

Cr	Cu	Mn	Fe	Mg	Ti	V	Zn	Si	Al
0.003	0.010	0.06	0.16	0.45	0.007	0.08	0.01	0.52	balance

Table 2. Mechanical properties of AA6061-T6.

Ultimate tensile strength (N/mm^2)	Yield strength (N/mm^2)	Elongation (%)	Hardness (Hv)
305	271	14	76.3



(a) (b)

Figure 1. FSLW tool (a) Schematic view, (b) Photographic view.

pin was slowly plunged into the work pieces till the tool shoulder comes in contact with the work piece and there were a mechanical interaction and velocity difference between the rotating tool and work piece where heat was produced by frictional work and material deformation. Lap welds were made in the longitudinal direction of the welding samples. The welded sample is shown in **Figure 2**.

The rotational speed, welding speed, and axial load were considered to be variables for the optimization of FSLW process. The parameters and its levels are shown in **Table 3**.

2.2. Lap-Shear (Tension-Shear) Tests

Lap-shear (tension-shear) tests were carried out as per ANSI/AWS/SAE/D8.9-97 [16] on a universal testing machine. **Figure 3** shows a typical lap-shear test specimen with is dimensions produced using friction stir lap welding. After welding, the joints were cross-sectioned perpendicular to the welding direction for tensile shear strength tests. The work pieces were polished to 1 μm finish.

For tensile property evaluation, lap shear tests were carried out covering the entire weld length. All tests were conducted on Instron 5500R testing machine as shown in **Figure 4**, at a constant cross head displacement rate of 5 mm/min.

The maximum load and failure location were recorded for each specimen. Tensile tests were carried out at room temperature at a crosshead speed of 1 mm/min. The welded area was located in the center of the tensile specimen. **Figure 5(a)** and **Figure 5(b)** show the FSW and shear tested samples. There would be numerous experiments that need to be carried out when there is a large number of parameters.

In order to solve this, the Taguchi Method helps to specifically design an orthogonal array survey and research the complete range of parameters with a small number of investigations. An L-9 orthogonal array with three levels and three factors was computed and implemented for conducting trials, as shown in **Table 4**.

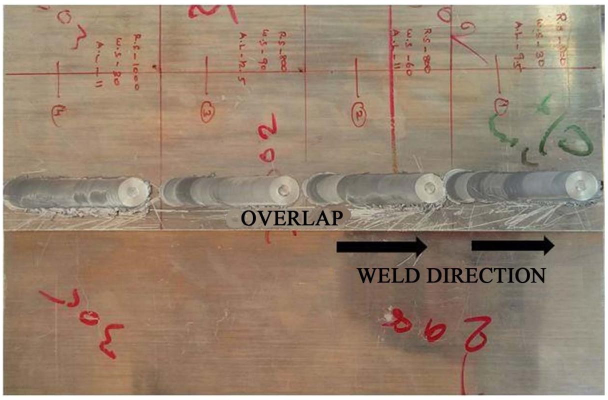


Figure 2. Welded sample.

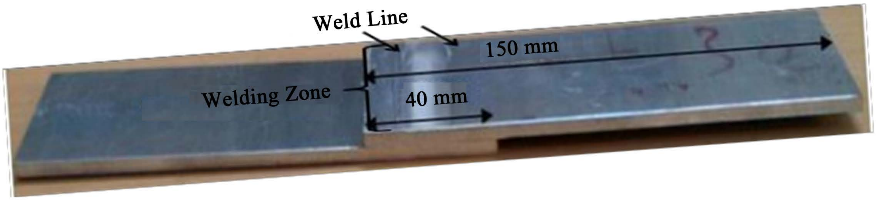


Figure 3. Lap-shear test specimen.

Figure 4. Tensile shear test machine along the entire weld length.

Table 3. Process parameters range and their levels.

Factor	Process Parameter	Level		
		1	2	3
A	Tool rotational speed (rpm)	800	1000	1200
B	Welding speed (mm/min)	30	45	60
C	Axial load (kN)	9.5	11	12.5

(a) (b)

Figure 5. (a) FSW samples, (b) Shear tested samples.

Table 4. L-9 Orthogonal array with response.

Factor	Process Parameter			Shear Strength (MPa)	S/N ratio
	Rotational Speed (rpm)	Welding Speed (mm/min)	Axial Load (kN)		
1	800	30	9.5	42.43	32.55
2	800	45	11.0	58.64	35.36
3	800	60	12.5	47.97	33.61
4	1000	30	11.0	36.42	31.22
5	1000	45	12.5	48.87	33.78
6	1000	60	9.5	38.32	31.66
7	1200	30	12.5	52.36	34.38
8	1200	45	9.5	55.42	34.87
9	1200	60	11.0	53.34	34.54

3. Results and Discussions

3.1. Signal to Noise (S/N) Ratio

In Taguchi method, the term "signal" indicates the desired value for the output characteristics and the "noise" indicates the undesirable value that signifies the output characteristics. The objective of the signal-to-noise ratio is to develop processes that are insensitive to noise. Process parameter setting with highest S/N ratio always yields the optimum quality with minimum variance. In general, signal-to-noise ratio signifies the ratio of mean to the standard deviation [17]. The quality of the welded joints is investigated by considering shear strength as the main characteristic feature. The S/N ratio and means for each of the process parameters were calculated to find the influence of process parameters on the response (shear strength). In this current work, the S/N ratio was chosen according to the proposition of "the larger-the-better" characteristics that indicate its robustness according to [18].

$$(\mathrm{S/N})_{\mathrm{HB}} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{T_i^2}\right) \tag{1}$$

where n is the number of the repetitions and T_i is the value of the shear strength of the test on that trail. The average response of S/N ratio and experimental data for each combination of the process parameters are given in Table 5 and Table 6.

3.2. Analysis of Variance

Analysis of variance (ANOVA) is a mathematical technique developed by Sir Ronald Fisher, which breaks the total variation down into accounted sources and delivers a way to interpret the results from actual experiments [19]. The test was performed to identify the statistically significant process parameters [20]. This analysis was carried out for a level of significance of 5%, *i.e.* for 95% confidence level. The ANOVA results of S/N ratio and means for shear strength are given in Table 7 and Table 8 respectively.

Table 5. Average response table for mean.

*Levels	Mean		
	Rotational Speed (rpm)	Welding Speed (mm/min)	Axial Load (kN)
1	49.68	43.74	45.39
2	41.20	54.31	49.47
3	53.71	46.54	49.73
Max-min	12.50	10.57	4.34
Rank	1	2	3

Table 6. Average response table for S/N ratio.

*Levels	S/N ratio		
	Rotational Speed (rpm)	Welding Speed (mm/min)	Axial Load (kN)
1	33.85	32.72	33.03
2	32.23	34.67	33.71
3	34.60	33.28	33.93
Max-min	2.37	1.95	0.89
Rank	1	2	3

(*Levels 1, 2 and 3 in Table 5 and 6 indicate that low, medium and high).

Table 7. ANOVA of means for shear strength.

Factor	Process parameters	Sum of squares	Degrees of freedom	Mean sum of squares	F-test
A	Rotational speed	244.401	2	122.20	16.21
B	Welding speed	179.994	2	89.99	11.94
C	Axial load	35.555	2	17.77	2.36
Error		15.075	2	7.53	
Total		475.025	8		

Table 8. ANOVA of means for S/N ratio.

Factor	Process parameters	Sum of squares	Degrees of freedom	Mean sum of squares	F-test
A	Rotational speed	8.821	2	4.41	17.68
B	Welding speed	6.071	2	3.035	12.17
C	Axial load	1.308	2	0.654	2.62
Error		0.498	2	0.249	
Total		16.700	8		

Statistically, there is a tool called an F-Test named to find the design parameters that have a significant effect on the quality characteristic. Usually, when F > 4, it means that the specific design parameter accounts for a significant effect on the quality attributes [21]. Hence, the rotational speed and the welding speed have the important impact on the quality attributes of the metal and the axial load is less significant. The contribution of the tool pin profile, rotational speed, and welding speed is shown in **Figure 6**. The most important factor that influenced the FSLW process was the tool rotational speed with a contribution rate of 51% while the percentage of error is 3%. The **Figure 7** shows two graphs, each of which represents main effects plot for Means and S/N ratio. Based on the highest values of the S/N ratio and Mean values, the overall optimum process parameters for shear strength are A3, B2, and C3.

The theoretical shear strength value for the optimum process parameters has been calculated from the following equation [11].

$$T_{\text{predicted}} = T_m + \sum_{i=1}^{n} \left(T_0 - T_m \right) \tag{2}$$

Tm is the mean response or means S/N ratio, T_0 is the mean response or mean S/N ratio at an optimal level and n is the number of design attributes that have an impact and affect the quality of the properties. Substituting the values in Equation (2), the predicted tensile strength is 61.358 MPa. The shear strength value for the optimum level of process parameters was 63.08 MPa.

4. Conclusions

In this investigation, the Friction Stir Lap Welding of AA6061-T6 alloy was carried out successfully. The results can be summarized as follows:

- The parameters affecting friction stir lap welding while joining AA6061-T6 alloy were studied. It is observed that rotational speed and welding speed have a revealing effect on shear strength.
- The percentage of contribution of FSLW process parameters was evaluated using ANOVA and found that the rotational speed, welding speed, and axial load contribute 51%, 38%, and 8% respectively.
- The optimum parameter combinations such as the rotational speed of 1200 rpm, welding speed of 45 mm/min and the axial load of 11.5 kN provided a shear strength of 63.08 MPa.

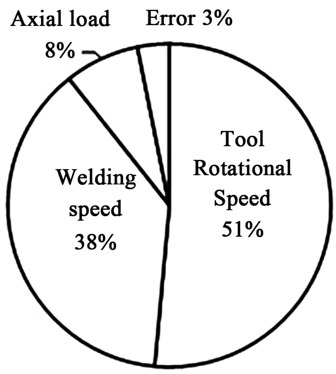
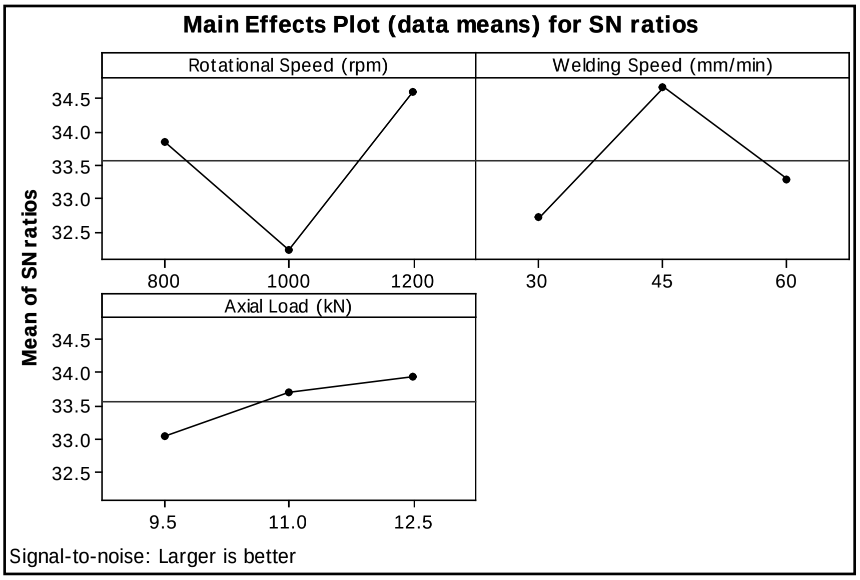
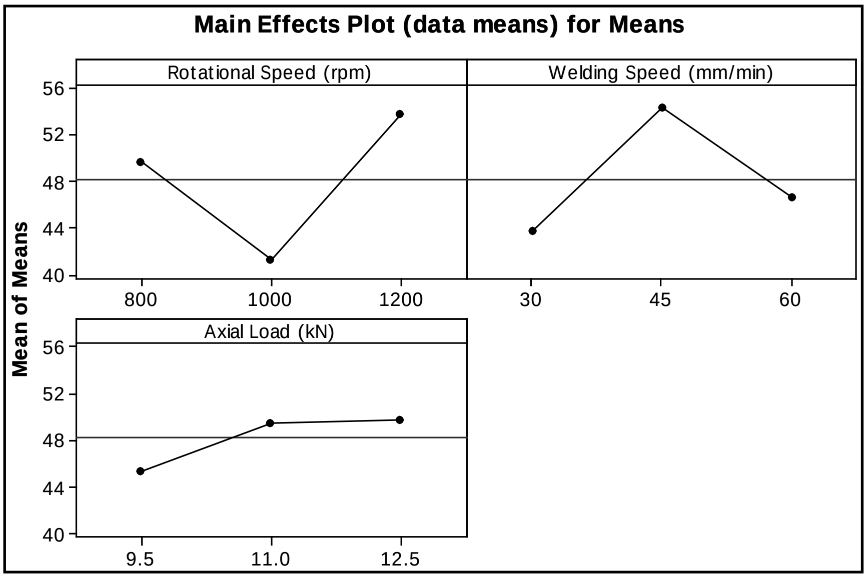


Figure 6. Percentage contribution of process parameters.



(a)



(b)

Figure 7. Main effects plot: (a) S/N ratio, (b) Means.

5. Scope and Future Work

Further investigations on the microstructure examined using Optical Microscopy (OM) and Scanning Electron Microscopy during friction stir lap welding for AA6061-T6 aluminum alloys at different conditions and for different process parameters might be very beneficial.

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