Parametric Optimization for Friction Stir Welding of AL 6063 Alloy Using Taguchi Technique

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Abstract- Taguchi approach and analysis of variance were applied to determine the most influential control parameters for the mechanical properties of the joints of friction stir welded AL 6063 alloy. The evaluation of the effects of process parameters such as tool rotational speed, translational feed and axial force on tensile strength and hardness of friction stir welded AL 6063 alloy were investigated in this study. On the analogy, nine experiments were performed based on L9 orthogonal array of Taguchi's methodology of three input parameters with three levels. Analysis of variance was employed to find the levels of significance of input parameters. The results indicated that translational feed has the greatest effect on tensile strength and hardness as well. The effects of translational feed was followed by rotational speed and axial force. The results were confirmed by further experiments.

Keywords – AL 6063, Friction stir welding, Tensile strength, Hardness, Taguchi technique, Analysis of variance.

I. INTRODUCTION

Friction stir welding (FSW) is a novel solid state welding process for joining metallic alloys and has emerged as an alternative technology used in high strength alloys that are difficult to join with conventional techniques. It was invented at The Welding Institute (TWI) of the United Kingdom in 1991 and was initially applied to aluminum alloys [8]. Friction Stir Welding is a recent technique that uses a non-consumable rotating welding tool to generate frictional heat and plastic deformation at the welding location while the material is in solid state [4]. It is an energy efficient, environmental friendly and versatile. It is considered to be the most significant development in metal joining in a decade. Therefore, many works about FSW has been reported [7].

1.1 Principle of Friction Stir Welding

The working principle of the process is shown in figure 1. A welding tool comprised of a shank, shoulder and pin is fixed in a milling machine chuck and is rotated about its longitudinal axis. The work piece, with square mating edges is fixed to a rigid backing plate, and a clamp prevents the work piece from spreading or lifting during welding. The half-plate where the direction of rotation is the same as that of welding is called the advancing side, with the other side designated as being the retreating side [3].

The rotating welding tool is slowly plunged into the work piece until the shoulder of the welding tool forcibly contacts the upper surface of the material. Then the tool is transverse in the desired direction while it is rotating. The rotation of the pin does the stirring action of the softened material which makes the material undergo intense plastic deformation yielding a dynamically re-crystallized fine and defect free grain structure. By keeping the tool rotating and moving it along the seam to be joined, the softened material is literally stirred together forming a weld without melting. The welding tool is then retracted, generally while the spindle continues to turn. After the tool is retracted, the pin of the welding tool leaves a hole in the work piece at the end of the weld. These welds require low energy input and are without the use of filler materials and distortion [2] [3].

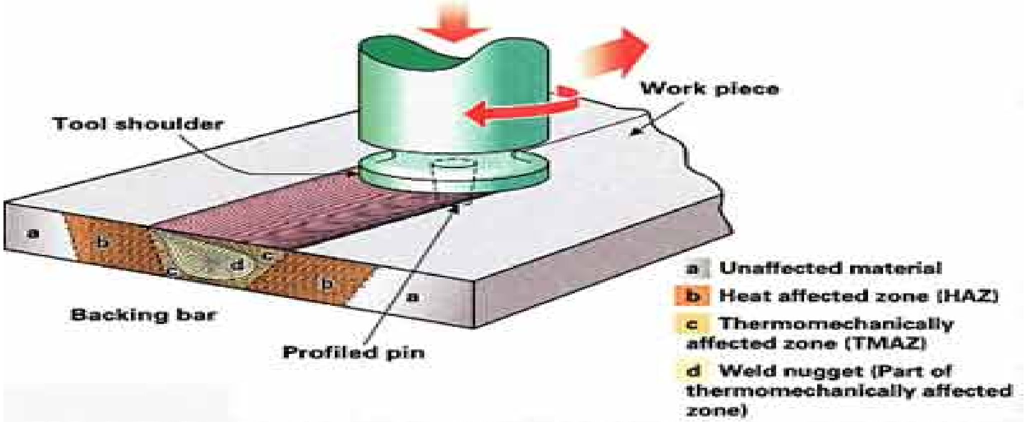

Figure 1. Schematic of friction stir welding

1.2 Need of Friction Stir Welding

Friction stir welding technology has been a major boon to industry advanced since its inception. In spite of its short history, it has found widespread applications in diverse industries. Hard materials such as steel and other important engineering alloys can now be welded efficiently using this process. The understanding has been useful in reducing defects and improving uniformity of weld properties and, at the same time, expanding the applicability of FSW to new engineering alloys. The demand of Aircraft Industries to substitute the conventional joining technologies with low costs and high efficient processes such as friction stir welding is considered as one of the most encouraging design challenge for the future.

II. LITERATURE REVIEW

The previous research was reviewed in order to show how this research contributes to the science of FSW. An emphasis is placed on work that relates to the topics of process parameters quantification. Aluminium has gathered wide acceptance in the fabrication of light weight structures requiring a high strength-to-weight ratio. The design of tool pin profile along with tool rotational speed, translational feed and axial force largely affect the properties of aluminium alloys.

C. Devanathan et al. (2013) described that friction stir welding has become very popular for joining of lightweight materials like aluminum, magnesium and its alloys. He discussed about the use of Taguchi experimental design technique for maximizing tensile strength of friction stir welded Al 6063 alloy. The effect of process parameters on tensile strength of welded joints were evaluated using ANOVA and signal to noise ratio of robust design. It was observed that the welding speed exhibited more influence on tensile strength of the welded joints followed by spindle speed and axial force [1].

M. Jayaraman et al. (2009) studied that in order to improve strength of welded joints in fusion welding of cast Al alloys, friction stir welding (FSW) technique may be employed to eliminate porosity, micro-fissuring, hot cracking etc. This paper discussed use of Taguchi experimental design technique for maximizing tensile strength of friction stir welded cast aluminium alloy A319. Using ANOVA and signal to noise ratio of robust design, effect on tensile strength of FSW process parameters were evaluated and optimum welding condition for maximizing tensile strength was determined [5].

A. K. Lakshminarayanan and V. Balasubramanian (2008) applied Taguchi approach to determine the most influential control factors which will yield better tensile strength of the joints of friction stir welded RDE-40 aluminium alloy. In order to evaluate the effect of process parameters such as tool rotational speed, traverse speed and axial force on tensile strength of friction stir welded RDE-40 aluminium alloy, Taguchi parametric design and optimization approach was used. Through the Taguchi parametric design approach, the optimum levels of process parameters were determined. The results indicated that the rotational speed, welding speed and axial force are the significant parameters in deciding the tensile strength of the joint [6].

III. METHDOLOGY AND EXPERIMENTAL WORK

3.1 Methodology

In the present study three process parameters such as tool rotational speed (A), translational feed (B) and axial force (C), which mostly contribute to heat input and subsequently influence the mechanical properties of the welded joints were selected in three different levels. The table 1 shows the process parameters and their levels.

Table 1. Process parameters and their levels

S. No	Parameter	Unit	Notation	Level		
				1	2	3
1	A	rpm	A	900	1000	1100
2	B	mm/min	B	42	55	68
3	C	kN	C	3	5	7

S. No.	Input Parameters		
	A	B	C
1	900	42	3
2	900	55	5
3	900	68	7
4	1000	42	5
5	1000	55	7
6	1000	68	3
7	1100	42	7
8	1100	55	3
9	1100	68	5

Table 2.Taguchi L9 Orthogonal array

The working ranges of welding parameters were finalized by the previous research work and conducting trial run. The satisfactory values obtained were used to conduct the experimental work. L9 orthogonal array was used for analysis purposes is shown in table 2.

3.2 Selection of Work Piece and Tool

The material under investigation was Al 6063 alloy having dimensions 6×50×65 mm (thickness × width × length) as shown in figure 2. Al 6063 alloy having chemical composition is shown in table 3.

Table 3. Chemical composition of specimen material Al 6063 alloy (wt. %)

Material	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Al 6063	0.2 - 0.6	0.35	0.1	0.1	0.45 - 0.9	0.1	0.1	0.1	Remainder

Figure 2. Al 6063 specimens to be welded

Figure 3. Designed tool

In the present work, the tapered pin cylindrical tool was used to perform the welding. The tool consists of the shoulder and tapered pin. The diameter of shoulder was taken 18 mm and length of pin 5.5 mm. Pin tapered with a shoulder end of 6 mm and tip end of 2.5 mm diameter as shown in figure 3.

3.3 Experimental Setup

Square butt joint configuration was prepared using a CNC vertical machine of 20 hp and 7500 rpm manufactured by Haas Automation, available at Central Tool Room, Ludhiana. The experimental setup of tool and workpiece on machine is shown in figure 4. The testing of welded pieces was carried out at Research and Development Centre, Ludhiana. The test specimens after the tensile test are shown in figure 5.


Figure 4. Experimental setup

Figure 5. Specimens after tensile test

IV. RESULTS AND DISCUSSIONS

The tensile strength and hardness which describes the quality of the FSW joints were accessed and the influence of welding parameters on the output response S/N ratio for each control factor was calculated. The S/N ratio was used to analyze the test run results because it represents both the average (mean) and variation (scatter) of the experimental results. In this investigation, maximum tensile strength was the objective function and larger the better S/N ratio was chosen as a larger S/N ratio corresponds to better quality characteristics.

4.1 Tensile Strength Analysis

Table 4. Process parameters and experimental results

Specimen Number	Process Parameters			Experimental Results		
	Spindle Speed [rpm] A	Translational Feed [mm/min] B	Axial Force [kN] C	Tensile Strength [MPa]	Signal to Noise Ratio	Joint Efficiency [%]
1	900	42	3	112.1	40.99	57.19
2	900	55	5	114.4	41.17	58.36
3	900	68	7	127.4	42.10	65.00
4	1000	42	5	115.8	41.27	59.08
5	1000	55	7	120.9	41.65	61.68
6	1000	68	3	129.4	42.24	66.02
7	1100	42	7	125.1	41.95	63.83
8	1100	55	3	127.0	42.08	64.80
9	1100	68	5	132.4	42.44	67.55

The nine experiments were performed based on the L9 orthogonal array. The effect of different parameters such as tool rotational speed, translational feed and axial force of Al 6063 alloy was analyzed. The observational values of tensile strength with their S/N ratios and joint efficiency are shown in table 4.

To avoid the extra calculations work, Minitab 17 statistical software [9] was used to calculate S/N ratio and plot the main effect graphs. Delta shows the common difference between the maximum and minimum values for the corresponding parameters. The generated response table 5 for signal to noise ratios given below shows the peak value of various parameters according to three different levels and it clearly determines the peak value ranks of parameters.

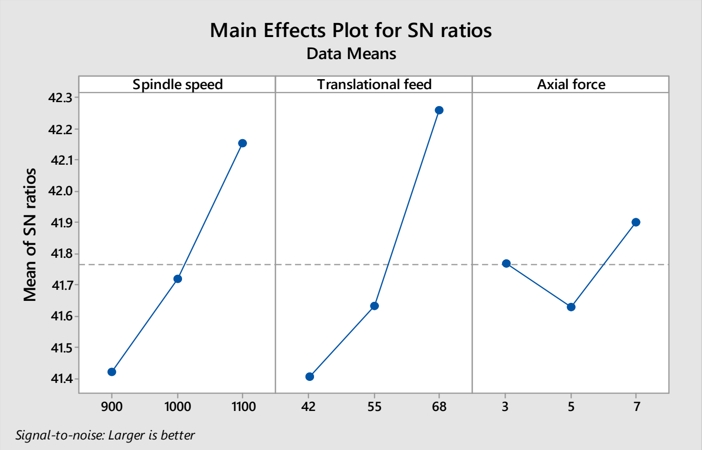

Table 5. Response table for signal to noise ratios

Level	Spindle Speed A	Translational Feed B	Axial Force C
1	41.42	41.40	41.77
2	41.72	41.63	41.63
3	42.15	42.26	41.90
Delta	0.73	0.86	0.27
Rank	2	1	3

Figure 6. Main effects plot for S/N ratio

It shows the main effects plot for S/N ratio indicating that tensile strength is maximum when spindle speed, translational feed, and axial force are at a level of A3 B3 C3 i.e. spindle speed at 1100 rpm, translational feed at 68 mm/min and axial force at 7 kN respectively.

Table 6 ANOVA table for tensile strength

Source of Variation	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean of Squares (MS)	Fisher ratio (F)	Probability value (P)	Percentage of Contribution (%)
A	2	0.81187	0.40594	32.32	0.030	38.15
B	2	1.18012	0.59006	46.97	0.021	55.45
C	2	0.11121	0.05561	4.43	0.184	5.23
Error	2	0.02512	0.01256			1.18
Total	8	2.12833				100.00

The percentage of contribution clearly shows in the table 6 that the translational feed 'B' is the most significant factor for the performed experiment with 55.45% of the total contribution. Rotational speed 'A' is at second place paying 38.15% of the contribution followed by the axial force 'C' of 5.23% of contribution. The value of R square model obtained from analysis is 98.82%.

4.1.1 Confirmation Test for Tensile Strength

Tensile strength = RS3 + TF3 + AF3 – 2(T)

Where, T is the overall mean of tensile strength in MPa

RS3 is the average tensile strength at second level of rotational speed at 1100 rpm

TF3 is the average tensile strength at second level of translational feed at 68 mm/min

AF3 is the average tensile strength at second level of axial force 7 kN

Substituting the values of various terms in equation,

Tensile strength = 128.17 + 129.73 + 124.47 − 2 × 122.72 = 136.93 MPa

The final step was verifying the improvement in tensile strength by conducting experiments using optimal conditions. Confirmation experiment was conducted at the optimum setting of process parameters. The rotational speed, translational speed and axial force were set at 1100 rpm, 68mm/min and 7kN respectively. The average tensile strength of friction stir welded Al 6063 was found to be 139.4 MPa that was within the confidence interval of the predicted optimal of tensile strength with the joint efficiency of 71%.

4.2 Hardness Analysis

The results of Hardness of Weld Zone (WZ), Parent Metal (PM) & Heat Affected Zone (HAZ) on different sets of combination of parameters were calculated according to the Brinell hardness (HB) in the table 7.

Table 7. Process parameters and experimental results

Specimen Number	Process Parameters			Experimental Results			Signal to Noise Ratio
	Spindle Speed [rpm] A	Feed [mm/min] B	Axial Force [kN] C	Hardness PM (HB)	Hardness TMAZ (HB)	Hardness HAZ (HB)	
1	900	42	3	71.6	48.2	63.7	14.16
2	900	55	5	71.7	49.3	64.4	14.53
3	900	68	7	72.2	50.6	64.9	15.13
4	1000	42	5	72.1	47.9	63.3	14.16
5	1000	55	7	71.8	48.9	64.1	14.41
6	1000	68	3	71.4	49.7	64.4	14.79
7	1100	42	7	71.7	47.1	62.6	13.99
8	1100	55	3	72.3	47.7	63.2	14.08
9	1100	68	5	72.2	48.9	63.8	14.56

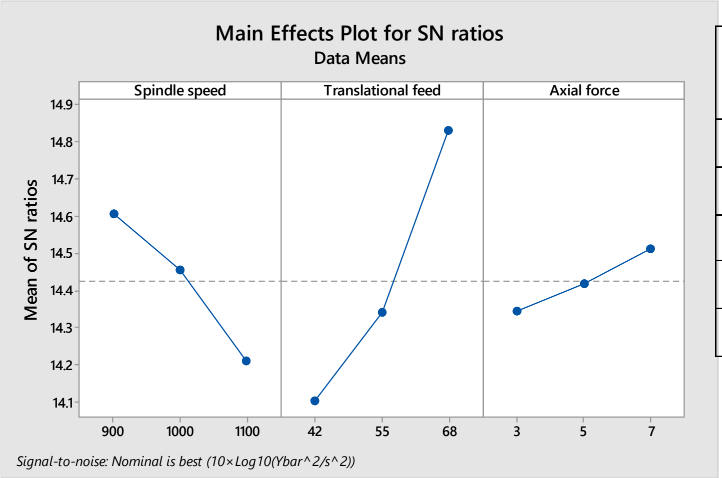

Figure 7. Main effects plot for S/N ratio

Table 8 Response table for signal to noise ratios

Level	Spindle Speed A	Translational Feed B	Axial Force C
1	14.61	14.10	14.34
2	14.45	14.34	14.42
3	14.21	14.83	14.51
Delta	0.40	0.73	0.17
Rank	2	1	3

The main effects plot for S/N ratio indicating that hardness is maximum when spindle speed, translational feed and axial load are at a level of A1 B3 C3 i.e. spindle speed at 900 rpm, translational feed at 68 mm/min and axial force at 7 kN respectively is shown in figure 7.

The percentage of contribution clearly shows in the table 8 that the translational feed is the most significant factor for the performed experiment with 73.85% of the total contribution. Rotational speed is at second place paying 21.41% of the contribution followed by the axial force with 3.84%. The value of R square model for the hardness analysis stands at 99.11%.

Table 9. ANOVA table for hardness

Source of Variation	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean of Squares (MS)	Fisher ratio (F)	Probability value (P)	Percentage of Contribution (%)
A	2	0.23881	0.119404	23.99	0.040	21.41
B	2	0.82353	0.411763	82.72	0.012	73.85
C	2	0.04287	0.021433	4.31	0.188	3.84
Error	2	0.00996	0.004978			0.89
Total	8	1.11515				100.00

4.2.1 Confirmation Test for Hardness

It must be noted that the above table 10 shows the combination of factor levels A1 B3 C3 are among the nine combinations tested for the experiment. This is expected because of the multifactor nature of the experimental design employed (9 from 3^3=27 possible combinations). Hence, there is no need of confirmation test to be carried out to check the hardness value.

V. CONCLUSION

The present investigation showed that butt joint configuration of Al 6063 aluminium alloy was successfully prepared using non consumable rotating tool with tapered cylindrical pin by friction stir welding technique. The samples were characterized for tensile strength and hardness of the welded joints. Taguchi technique and ANOVA was performed to investigate the significance of the process parameters. The following conclusions were made.

- The optimal FSW process parameter combinations are spindle rotational speed at 1100 rpm, translational feed at 68 mm/min, axial load at 7 kN at which maximum tensile strength was achieved.
- The maximum of 71% joint efficiency was achieved for the optimum process parameters. It clearly means that tensile strength of the weld joint was almost 71% of the tensile strength of the parent metal.
- The percentage of contribution of FSW parameters was calculated for tensile strength. It was found that the translational feed has the maximum contribution of 55.45% and rotational speed at second place of 38.15% contribution followed by the axial force with minimum effects of 5.23% on tensile strength when compared to other factors.
- Hardness directly varies in relation to the translational feed and indirectly varies to the rotational speed.
- Hardness drop was observed in the weld region. The softening was evident in the in the heat affected zone on advancing side of the weld comparatively to the retreating side. Being observatory to this zone, as it corresponds to failure location in the welds.
- The optimal FSW process parameter combinations are spindle rotational speed at 900 rpm, translational feed at 68 mm/min, axial load at 7 kN at which maximum hardness was achieved.
- The percentage of contribution of FSW parameters for hardness was calculated. It was found that translational feed has the maximum contribution of 73.85% and rotational speed at second place of 21.41% contribution followed by axial force of 3.84% on hardness when compared to other factors.
- Smooth quality welds obtained at high rotational speed and low translational feed.
- Low plunging force of tool was required and tool breakage was avoided with the help of tapered cylindrical pin profile.

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