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Analysis of Tensile Strength of Friction Stir Welding for Aluminum Alloys AA6061 with AA5083 Using Design of Experiment Approach

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ABSTRACT

The analyzing of friction stir welding is applied to AA6061 with AA5083 using design of experiment (DOE) in Minitab to get optimization of the tensile strength. The analyzing was achieved by varying the main parameters as rotational speed by the values 700, 1050, and 1400 R.P.M, linear velocity of 40, 60, and 80 mm/min and pin depth of 3.5, 3.6, and 3.7 mm less than thickness material weld. A total of 11 runs were included corresponding to the designated experimental design. Analysis of variance (ANOVA) software was used to procedure for full factorial design with 1 replicate and 3 center points analysis. The results clarified that the rotational speed parameter is more significant to be controlled rather than the linear velocity and pin depth of tool. Decreasing rotational speed and increasing linear velocity and pin depth led to higher tensile strength. The profiles welded at 700 RPM, 80 mm/min and 3.7 mm had achieved the optimum case to get the value of maximum tensile strength. It is concluded that the rotational speed was the key parameter that manipulate the tensile strength in friction stir welding applied to AA6061 with AA508.

1. INTRODUCTION

The structural strength and lightweight properties of aluminum have a significant impact on the construction process through their use as structural material in the automotive and aerospace industries, making aluminum one of the most significant metals in our modern society [1, 2]. The earliest welding operations can be found in the Middle East and Europe during the Bronze and Iron Ages. The welding definition is joining two material or more by using heat or pressure with heat or pressure as friction welding. Welding processes are classified to brazing welding, resistance welding, gas welding, arc welding, solid state welding and other processes welding [3].

Friction stir welding (FSW) is a solid-phase welding technique that has been used to weld 6000 series aluminum alloy for rail rolling stock and has been used to weld 2000 series and 7000 series aluminum alloy for aircraft which had been challenging to weld using previous welding method [4, 5]. FSW has emerged as one of the vital alternative technologies which has good potential to use in major industries like automobiles, aerospace, shipbuilding, railways and can be used in high strength alloys [6].

The advantages of FSW are that the work pieces to be joined are not molten compared to traditional welding methods, such as electric arc welding, and thus avoid many defects in melting state welding [7]. FSW is capable enough to produce welds of high quality with no defects, reduced cost and lower environmental impact when compared to traditional fusion welding which carries the common problems, such as solidification, liquation cracking and porosity [8]. As the composite materials have hardness, rigidity, fatigue strength, flexural strength, modules of rigidity, FSW is very suitable for the composite material.

Because FSW joints have a high joint efficiency, excellent fatigue strength, and little residual stress and deformation in comparison to traditional fusion welding techniques like laser welding and arc welding [9, 10]. The method is increasingly being used in a variety of industrial fields, principally those involving cars, trains, ships, and airplanes. The aerospace and naval industries have expressed interest in using materials with high mechanical properties and low density [11, 12].

Before introducing DOE, it is necessary to know what an experiment is. An experiment is an approach or procedure, based on scientific grounds, to validate a hypothesis or to confirm an existing fact or already proclaimed findings [13]. After conducting experiments, Lenth [14] is left with large set of data which he needs to look into carefully and arrive to a conclusion. If he is not successful in retrieving the information from the output data, then the sole purpose of conducting an experiment goes in vain. DOE is an efficient tool to draw maximum and possibly correct level of information from the set of experimental data; it also gives insight into the effect of each factor on the outcome of the experiment. However, DOE is a series of tests where intentional changes are done to factors that are considered to influence the outcome of interest (response) from the experiment [15]. DOE is effectively used in various fields of engineering where optimum condition is obtained for good efficiency of the process.

This study optimizes process parameters in FSW on dissimilar aluminum alloys to enhance tensile strength performance. The primary goal of this study is to achieve the highest possible joint material strength. High-strength joints are expected to be more weldable and efficient among alloys. A strong joint with no geometric defects or mechanical failures is crucial for the industry.

In the application of DOE, the analysis of variance (ANOVA) is an essential method in developing and accessing the relevancy of the model. ANOVA presents a structured analysis of results. The relationship between and within the models and all the parameters analyzed are represented in ANOVA. In the studies [16, 17], the effect of the chip's surface topography on the weld strength through the hot extrusion experiment was analyzed using the 2^k factorial design. The authors proposed that the 2^k factorial design was the most appropriate design for experimental investigation. The design was used to screen out the most crucial parameters to be considered for further optimization. The advantage of using DOE is to save materials, time and financial resources [18].

By using the optimum process parameters, friction stir welding is a promising technique that produces joints with high tensile strength and few defects. Hence, this work investigated the weld ability by utilizing friction stir welding of aluminum alloys AA6061 with AA5083 to investigate the effect of the rotational speed, linear velocity and depth of pin of the tool on the welded part on the mechanical properties by analytical method by using DOE in Minitab software.

2. MATERIALS AND METHODS

2.1 Specimen preparation

Two aluminium alloys AA5083 and AA6061 are chosen to be welded together using the butt friction stir technique. The chemical composition and mechanical properties of these alloys are shown in Tables 1-3. Using a cutting machine, each aluminium alloy plate was cut to the dimensions 65 mm length ×50 mm width ×4 mm thickness. Then, oxidation was removed using a metal polishing brush. To create the FSW joints of the dissimilar aluminium alloys, a longitudinal butt joint arrangement perpendicular to the direction of rolling was prepared. To fix the plates to be welded on the milling machine, a fixture and backing steel plate were made specifically for this purpose.

Two prepared pieces of AA6061-AA5083 aluminium alloy plates were placed butt-to-butt without gap, joined in three steps as follows: first step involves plunging, second step involves stirring and welding, third step involves retracting the welding tool.

FSW processes were performed with various welding parameters including tool rotational speed of 700, 1050, and 1400 RPM. linear velocity of 40, 60, and 80 mm/min and the depth of pin of the tool on the welded part is 3.5, 3.6, and 3.7 mm, plunging and dwelling time is 30 sec remaining constant. Effects of parameters such as the tool's rotational speed, linear velocity, and pin depth on the welded part are included in the analysis.

Table 1. Composition of alloy 6061 (ASTM B221M-13 [19])

Element	Percent (WT %)
Magnesium (Mg)	0.80-1.20
Silicon (Si)	0.40-0.80
Iron (Fe)	0.0-0.70
Copper (Cu)	0.15-0.40
Chromium (Cr)	0.04-0.35
Zinc (Zn)	0.0-0.25
Titanium (Ti)	0.0-0.15
Manganese (Mn)	0.0-0.15
Others (Total)	0.0-0.15
Other (Each)	0.0-0.05
Aluminium (Al)	Balance

Table 2. Composition of alloy 5083 (ASTM B221M-13 [18])

Element	Composition (wt. %)
Al	92.4-95.6
Cr	0.05-0.25
Mg	4-4.9
Mn	0.4-0.1
Cu	Max 0.1
Fe	Max 0.4
Si	Max 0.4
Ti	Max 0.15
Zn	Max 0.25
Other, each	Max 0.05
Other, total	Max 0.15

Table 3. Mechanical properties of basic AA6061 and AA5083 (ASTM B221M-13 [18])

Material	Yield Stress (MPa)	Tensile Strength (MPa)	Elongation (%)	Hardness (HB)
AA6061	240	260	8	95
AA5083	110	270	12	109

2.2 DOE and ANOVA method

Software Design Minitab was used to perform design of experiment (DOE) method. There are two stages involved in using Minitab. In the first stage, experiments are conducted using a full factorial design with three parameters. For the second stage, ANOVA analyses to investigate the plots of main effect and interaction were applied. Effects of parameters such as the rotational speed, linear velocity, and pin depth on the welded part are included in the analysis. The values of the experimental design of the friction stir welding parameters and their levels is shown in Table 4.

Table 4. Design scheme of parameters and their levels

Parameter Symbol and Units	Level		
	Low (-1)	Centre (0)	High (+1)
Rotational speed (RS) (R.P.M)	700	1050	1400
Linear velocity (LV) (mm/min)	40	60	80
Pin depth (PD) (mm)	3.5	3.6	3.7

The input variables on the DOE are represented with the three levels for each parameter and an analysis run on 2^k full factorial design by three center points analysis consideration. The number of experiments suggested from Minitab was 11 runs as presented in Table 5. The analysis by Pareto chart and the main effect plot was applied to check the significant parameter and the impact of the parameters on the response. An analysis of the response optimizer is produced by DOE for tensile strength and the goal of the used parameters optimization is to achieve the highest tensile strength.

Table 5. Experimental design from DOE

Std Order	Run Order	Center Point	Blocks	RS (RPM)	LV (mm/min)	PD (mm)
1	2	1	1	700	40	3.5
2	10	1	1	1400	40	3.5
3	6	1	1	700	80	3.5
4	7	1	1	1400	80	3.5
5	8	1	1	700	40	3.7
6	11	1	1	1400	40	3.7
7	4	1	1	700	80	3.7
8	3	1	1	1400	80	3.7
9	5	0	1	1050	60	3.6
10	1	0	1	1050	60	3.6
11	9	0	1	1050	60	3.6

2.3 Tensile test

In this work, a tensile strength (TS) test was performed to obtain the mechanical strength of welding AA6061 with AA5083. Specimens for the tensile test are made according to the ASTM-E8M-04 standard as illustrated in Figure 1. It is very important that the surface of the joint for the specimen should be extremely smooth to get good results for tensile strength test as recommended by the studies [20, 21]. Tensile test was carried out with Testometric TM M500 100 kN tensile test machine and speed of 1 mm/min. The sample was under tension-tension load.

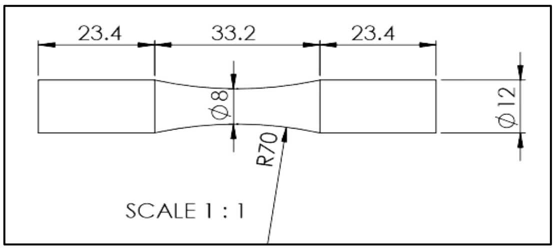

Figure 1. Tensile specimen dimension (mm) ASTM-E8M-04

3. RESULTS AND DISCUSSION

Tensile strength results, presented in Table 6, revealed an inverse relationship between tensile and rotational speed for all welded samples. The result presented was used to analyze the relationship between the three input factors, RS, LV and PD and the response (tensile strength). The minimum rotational speed supported the peak tensile strength. To test the model's effect of curvature, three center points were incorporated into the design, and the interactions between parameters were also considered. The result of tensile strength is used as a measure of the quality of the material. The tensile properties are also used as a measuring parameter to determine the areas of application of new materials and processes like aluminum alloys. The data shows that the minimum rotational speed with maximum linear velocity and pin depth provide the high resulting tensile strength. By supporting ANOVA of DOE explanation, the discussion is carried out.

Table 6. DOE result and tensile strength data

Std Order	Run Order	Center Point	Blocks	RS (RPM)	LV (mm/min)	PD (mm)	TS (MPa)
1	9	1	1	700	40	3.5	120.0
2	11	1	1	1400	40	3.5	84.05
3	2	1	1	700	80	3.5	188.8
4	7	1	1	1400	80	3.5	108.8
5	4	1	1	700	40	3.7	162.0
6	6	1	1	1400	40	3.7	97.6
7	5	1	1	700	80	3.7	199.8
8	3	1	1	1400	80	3.7	138.4
9	10	0	1	1050	60	3.6	114
10	1	0	1	1050	60	3.6	141.0
11	8	0	1	1050	60	3.6	133.4

The heat generated during friction stir welding comes from the friction between the tools rotating on the stationary workpiece. The generated heat affects the mechanical behavior of the joints. The tensile test results elucidate that the highest ultimate tensile strength of 199.819MPa occurred at the lowest rotational speed. As the temperature increases due to the increase in tool rotational speed, there is a decrease in the ultimate tensile strength across the welds. This decrease could be as a result of coarsening or dissolution of precipitates at the weld zone due to higher heat generation which results in weak bonding at the weld zone. On the hand, the high tensile stress was obtained from parameters L.V 80 mm/min with P.D 3.7 mm, and the relationship is linear, meaning that whenever feed rate and the pin depth are increase, the output the maximum tensile stress also increases. The above findings were similar to those commented on by the studies [22, 23].

The result of ANOVA revealed that the significant terms influencing tensile strength in the friction stir welding of AA6061 with AA5083 are rotational speed and linear velocity, they indicated by the value $p<0.05$ as illustrated in Table 7 and Figure 2 (Pareto Chart), but the rotational speed factor has a greater impact on tensile strength than the linear velocity. The remaining terms, pin depth and interaction between factors are insignificant.

Table 7. Analysis of variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	2828	1603.47	8.26	0.112
Linear	3	12164	4054.58	20.88	0.046
R.S	1	7301.9	7301.88	37.61	0.026
L.V	1	37067	3706.78	19.09	0.049
P.D	1	1155	1155.07	5.95	0.135
2-Way Interactions	3	250.2	83.41	0.43	0.755
R.S*L.V	1	210.4	210.37	1.08	0.407
R.S*P.D	1	12.2	12.18	0.06	0.826
L.V*P.D	1	27.7	27.68	0.14	0.742
3-Way Interactions	1	275.6	275.56	1.42	0.356
R.S*L.V*P.D	1	275.6	275.56	1.42	0.356
Curvature	1	138.2	138.23	0.71	0.488
Error	-	2	388.3	194.17	

The affirmed by the ANOVA outcomes, the value of R-square (R^2) is over 97%. As a result, the model is taken into consideration to be statistically significant.

In DOE analysis, it is substantial to examine the magnitude of error in order to avoid the influences of the nuisance parameters that are not incorporated in the analysis. This can be understood by evaluating the observed data normality, where the data distribution must be produced normally. It can be seen that the residuals' normal probability plot for tensile strength is very close to the straight line as shown in Figure 3. It indicates that the errors are within tolerable margin with a lack of fit of F-value is very low and negligible, hence normally distributed.

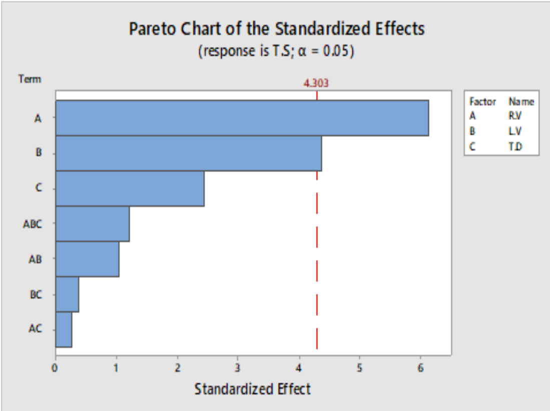

Figure 2. Pareto chart

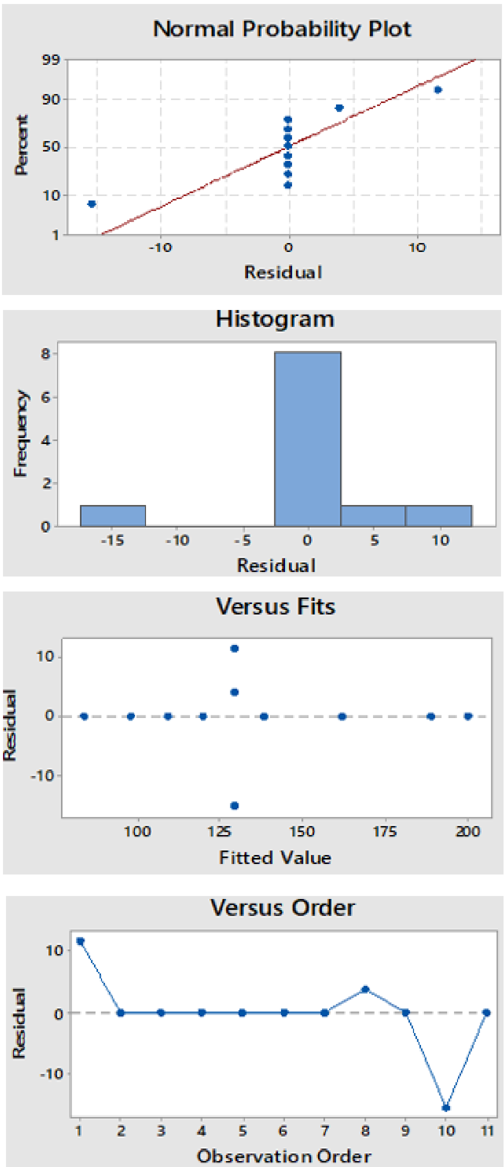

Figure 3. Residual plots of tensile strength

For residuals versus fits response, the random scatter of points about zero can be observed and the resulted pattern indicate that only three (3) out of the eleven (11) values were far from the remaining eight (8) samples. This means that the model developed through this curve fitting represent the group of data and fits well. Similarly, the scattered points indicates that the model satisfies the prediction of the ANOVA, and the regression model fits the observed values reasonably well. The histogram of residuals seems to be approximately symmetric skewness about the mean, which indicates that the data are normally distributed.

The main effects plot can be observed from ANOVA analysis as given in Figure 4. It illustrates that the lines connecting the mean of the tensile strength from low to high values set of three parameters is close to the overall center points. An interaction plot can be observed in Figure 5; the same trend is described, demonstrating that the final model selected is appropriate for the data being observed. On the other hand, the results of ANOVA in Table 7, where the curvature case's p-value was greater than 0.05, confirm that the curvature effect is unimportant in terms of the response finding. As a result, the curvature model cannot adequately fit all the data.

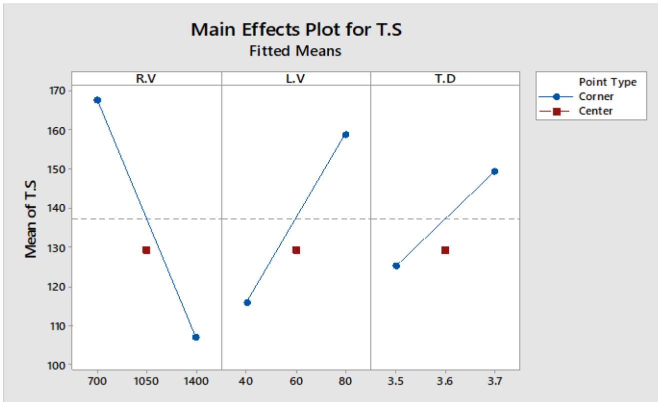

Figure 4. Main effects of the plot of tensile strength

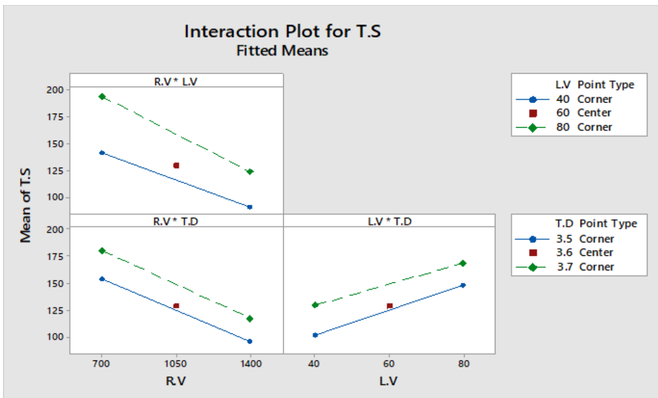

Figure 5. Interaction plot of tensile strength

The optimization process by response optimizer analysis is used to determine which parameter has an impact on products and how that parameter affects the response of tensile strength. Through the response optimizer method, the best tensile strength value was determined. An analysis of the optimizer's response derived from DOE for tensile strength is shown in Figure 6. The optimization of the experiment aims to have a high response. The results of the experiments demonstrated that the suggested rotational speed of 700 R.P.M, linear velocity of 80 mm/min, and pin depth of 3.7 mm produced a high tensile strength of 199.8MPa.

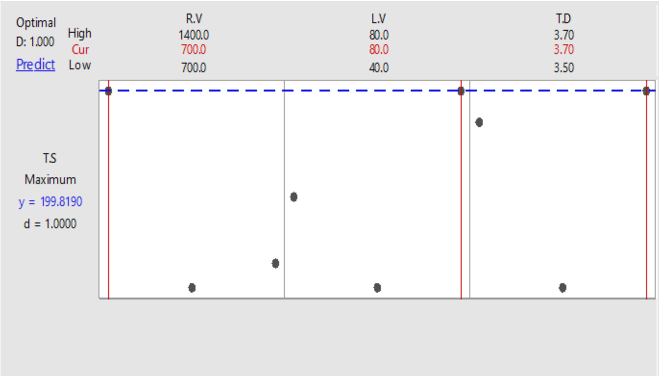

Figure 6. Optimization plot

4. CONCLUSION

The aim of this research was to investigate the tensile strength in friction stir welding of aluminum alloys AA6061 with AA5083. The main part of this project is concerned about investigating the effect of parameters (the rotational speed (RS), linear velocity (LV) and pin depth (PD) of AA6061 with AA5083 in friction stir welding on the tensile strength by DOE analyzing and ANOVA method. The following deductions were done following the objectives of this work:

- The ANOVA revealed that factor A (rotational speed (RS)) is the most influential parameter on the response, followed by B (linear velocity (LV)) that is less significantly affecting the response.
- The rotational speed is key in determining the mechanical properties in friction stir welding applied on AA6061 with AA5083 and the effect of this parameter provides a contribution to response (tensile stress).
- The optimization of the experiment aims to have a high response. Results of the experiments showed that the suggested rotational speed of 700 R.P.M, the linear velocity of 80 mm/min and pin depth of 3.7 mm gave the high tensile strength of 199.8MPa.
- The work focused on Friction stir welding (FSW) which emerged as one of the vital alternative technologies with high joint efficiency, and the result was characterized by high tensile strength of the weld joint, which has good potential to use in a variety of industrial fields like automobiles, aerospace, shipbuilding, railways.

It is recommended that future work focuses on FSW for different aluminum alloys with other welding parameters, such as geometry and design of tool and indentation time of tool and it also focuses on other mechanical properties, such as fatigue behavior on welding materials. Among these, the most essential is the application of artificial intelligence (AI) techniques to select the optimum FSW parameters for aluminum welding.

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NOMENCLATURE

FSW	Friction Stir Welding
DOE	Design of Experiment
ANOVA	Analysis of Variance
AA	Aluminum Alloy
RS	Rotational Speed, R.P.M
LV	Linear Velocity, mm/min
PD	Pin Depth, mm
TS	Tensile Strength, MPa