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Investigation of optimum parameters for rotary friction welding of aluminum round bars using three-level factorial design methodology

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Abstract

The welding process has been essential to increasing productivity in numerous industries across Thailand. There are several welding processes to choose from, and the welding process to use will be determined by the suitability of the production in that industry. Another important consideration in welding is to keep the mechanical properties of the joint area as close to the parent material workpiece as possible. This research aims to select the optimum parameter for rotary friction welding aluminum round bar AA6063-T5. That is according to the DIN 50125 type B standard test. The optimal condition consists of welding rotational speed, welding time, and welding pressure rated. The experiment used a three-level factorial design (3^k). By a 95% confidence, all of the factors studied had a significant impact on rotary friction welding. A rotational speed of 2,000 rpm, a welding time of 26.97 sec and a pressure of 30 bar resulted in a maximum weld strength of 179.148 MPa.

1. Introduction

Nowadays, the welding process plays an important role in the development of various industries in the country, such as the ship-building industry, automotive industry, aerospace industry, etc. There are several methods of welding processes, and the selection of the welding process will depend on the suitability of the production in that particular industry. The conventional welding were usually done using the principle of heating until the workpiece melts in a homogeneous metal. However, the joint after welding will form a new structure and may not be the same as the original metal structure. Which can reason residual stress, distortion, crack during melting and porosity. In addition, another important problem in welding is to keep the mechanical properties of the joint area as close to the parent material workpiece as possible. Including control of the heat-affected zone (HAZ) may damage the parts or use poor performance. In other words, depending on the welding material used and the welding process parameters, welding aluminum could increase or decrease its properties compared to the original metal. Even, the fusion welding processes that control the thermal effects well generate joints that are inferior properties to that of the base metal [1,2].

As a result, rotary friction welding processes have been developed, which are non-melt welding. Rotary friction welding is the oldest friction joining process [3] and it were patented by The Welding Institute (TWI) in the UK in 1991 [4,5]. The rotary friction welding is the most popular method, where one workpiece is rotated as the two workpieces are brought together under friction pressure. This method is a solid-state process for joining materials by close contact with a plasticized interface. The rotary friction welding has been used extensively in manufacturing methods as it reduces HAZ and increases good mechanical properties [6]. As no fillers are utilized, metallurgy issues are avoided [7]. Which the welding temperature is lower than the melting point of the workpiece, the heat is generated by the friction coefficient of the interface. Welded joints have the main advantage of not having casting defects in the weld zone [8]. One of the most important advantages of this process is that it can be used to join materials that are identical or dissimilar. In particular, materials that are difficult to weld in general such as copper, brass, aluminum alloys of various grades. The microstructure obtained from rotary friction welding is characterized by a fine grain, high tensile strength. The tensile strength in the center of the weld is higher than the edge of the weld and higher than the tensile strength of the parent material [9,10]. Aluminum alloys were one of the most popular materials utilized in rotary friction welding processes for industrial applications due to its low cost, high workability, and good weldability. In the previous literature [2,5,9,11,12], the authors explained the experimental study of the process of rotary friction welding for aluminum alloys. Alves *et al.* [2] and Kimura *et al.* [11] proposed using a rotary friction welding process to join aluminum alloys to stainless steels. The findings revealed that the two metals could join with one another. However, the results of the tensile test revealed that the pull caused a rip in the aluminum alloy body location. Subsequently, Abd-Ali *et al.* [12] conducted an experiment that compared aluminum friction welding to carbon steel friction welding. The results revealed that the maximum hardness was found near the center of the weld, which was confirmed by a microstructural evaluation of the weld interface, which revealed that the maximum tensile strength of weld was also found there [9]. Meengam *et al.* [5] proposed variables affecting the welding of aluminum alloy 7075, concluding that rotation speed, burn of length, and weld time was all essential factors in the rotary friction welding process.

Most recently, Mullo *et al.* [13] have used the design of experiment to investigate the effect of laser heat treatment on mechanical performance and microevolution of aluminum alloy joints during rotary friction welding. Lashgari *et al.* [14] investigated the micro-structure, tensile properties, hardness, wear resistance, and corrosion properties of solid cylinder weld joints in a rotary friction weld of additively manufactured stainless steel. Nu *et al*. [15] examined how rotary friction welding parameters influence alloy micro-hardness and joint strength. If the diameter of the weld part is less than 15 mm, studies have shown that changing the rotation speed significantly has a little influence on the welding quality. It is clear that researchers are continuing to be interested in friction welding research. In addition, Mercy *et al.* [16] have proposed a technique for improving mechanical properties by utilizing analysis of variance (ANOVA) to apply statistical solutions to the best response for the process.

Moreover, research has been found to propose a method for optimizing rotary friction welding process parameters using experimental design [1,5,17]. Similarly, manufacturing process optimization were quite successful in several industries through experimental design methodology. It is well known that the bond strength at the interface is an important criterion to evaluate the mechanical properties of the rotary friction welding materials [9]. Therefore, this paper focuses on the investigation of optimum parameters affecting the ultimate tensile strength of welds obtained for rotary friction welding of aluminum round bars AA6063-T5 by using a three-level factorial design methodology.

2. Experimental

2.1 Material properties

The experimental material in this research is AA6063-T5 aluminum alloy round bars. Which have good joint efficiency and good bend ductility after rotary friction welding [9], and it is also the most widely used grade in the industry. The chemical composition and ultimate tensile strength were shown in Table 1. Before welding, the workpiece was machined (Turning) into a cylindrical shape with a diameter of 12 mm and a length of 85 mm.

2.2 Rotary friction welding

It is known that rotary friction welding is non-fusion welding. Therefore, the workpiece obtained from this type of welding still contains the mechanical properties of the original metal structure. It appropriate for welding applications that need to be free from HAZ. In the methodology of rotary friction welding, that one part is stationary while being forced to rub against another rotating part under axial pressure. Both parts rotate around the longitudinal axes in the same pattern at the same constant angular velocity. The longitudinal axes of the two parts are parallel and slightly interface [19]. Across the experiment, the researcher maintained complete control over all conditions using the following procedures: The welding rotation speeds are 860 rpm, 1400 rpm and 2000 rpm, respectively, and are controlled by the lathe machine. The welding time parameter control section includes three levels: 10 sec, 20 sec, and 30 sec, respectively, and the clamping system of workpiece 2 was connected to a hydraulic pressure system that could adjust the pressure as required. The three levels of the experimental design were 10 bar, 20 bar, and 30 bar, respectively. The lathe machine was designed by modifying used for stability and precision together with a hydraulic servo valve that controls axial forces.

A schematic diagram of the experimental set-up of the rotary friction welding were shown in Figure 1. The heat were generated as a result of the friction between the materials while the friction is applied to the parts, causing both metals are fused. The welding process is carried out according to the purpose of each order design. The workpiece becomes one when the metal has cooled, the pressure in the cylinder has been reduced, and the rotary friction welding process has been completed.

2.3 Tensile testing

The workpiece from rotary friction welding has followed the case of the three-level factorial design methodology. After the welding process, the workpiece were machined perpendicular to the weld line, that the joint were centered on the specimens. The specimen were a solid round bar from aluminum alloy AA6063-T5 with dimension according to the standard test DIN 50125 type B as shown in Figure 2. After that, the workpiece will be thread rolled with size M12 for the specific area of grip in the tensile test. Under uniaxial tensile test conditions in Figure 3, the test results provide information on the ductility and strength of the materials. These details are useful for comparing welding parameters for enhancing the mechanical properties of joints and quality control under specific conditions.

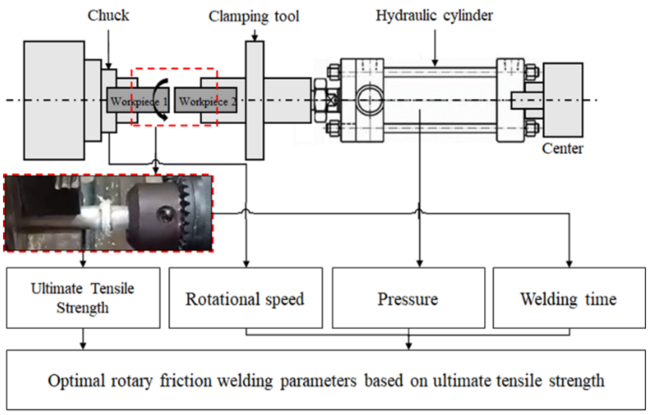

Figure 1. Schematic diagram of experimental setup of the rotary friction welding operation.

Table 1. Chemical composition and ultimate tensile strength of AA6063-T5 aluminum alloy.

Chemical composition (wt%) [18]										Ultimate tensile strength (MPa)
Al	**Cr**	**Cu**	**Fe**	**Mg**	**Mn**	**Si**	**Ti**	**Zn**	**Other**	
Bal.	0.10	0.10	0.50	0.60	0.10	0.45	0.15	0.20	0.15	186

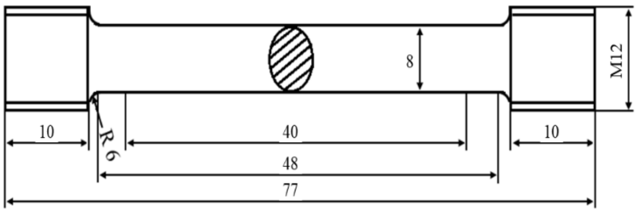

Figure 2. Specimen of the tensile test according to DIN 50125 type B.

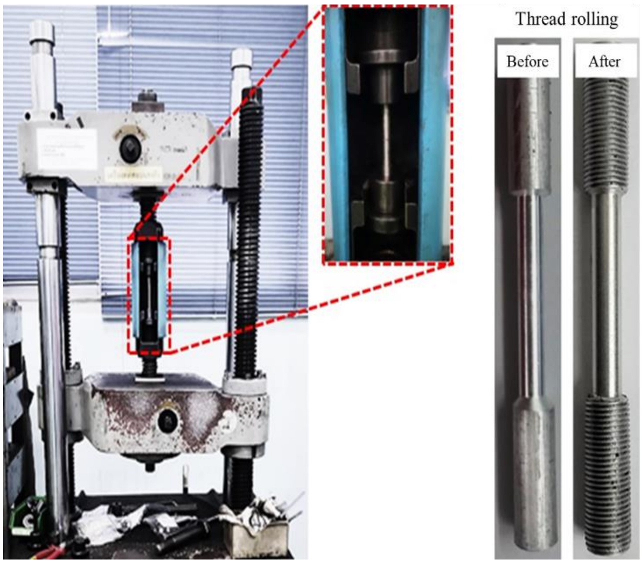

Figure 3. Universal testing machines and rotary friction welding specimen before thread rolling and after thread rolling.

2.4 Determination of experimental factors

In this work, the experimental design focused only on the successfully rotary friction welding process. This corresponds to the use of experimental machinery that can be adjusted for all levels of factors in the experiment. All welds were manufactured using machines and equipment that controls various parameters, which was optimized by ultimate tensile strength in the previous study. The rotary friction welding parameters in this work were rotational speed, welding time and internal pressure of hydraulic cylinder. These parameters could successfully influence frictional connection, more details can be found in [5,9]. The process parameters and the ranges examined in this work are given in Table 2

2.5 Design of experiment

The statistically designed experiments are simulation runs with specific process parameters and implemented using experiments. This is a method that investigates the significant parameters of a response and is efficient and ideal for determining the effective parameters [19]. To obtain an accurate estimate of the experimental error, each trial the condition was applied in random order. Moreover, this design has several advantages such as fewer experiment trials and data analysis using graphical methods. In this work, rotational speed, welding time and internal pressure of hydraulic cylinder were found to be the independent variables. The ultimate tensile strength were defined as the corresponding responses. According to the three-level factorial design, three parameters with three levels are considered, 27 sets of experimental conditions are presented in Table 3.

Table 2. Parameters and their respective levels.

Parameters	**Units**	**Level**		
		1	**2**	**3**
Rotational speed	rpm	860	1400	2000
Welding time	second	10	20	30
Pressure	bar	10	20	30

Table 3. Experimental design.

Run Order	**Rotational speed (rpm)**	**Welding time (second)**	**Pressure (bar)**
1	1400	10	20
2	860	10	10
3	860	30	20
4	2000	10	10
5	2000	30	20
6	1400	20	10
7	1400	30	30
8	2000	30	10
9	1400	30	10
10	1400	10	10
11	1400	20	20
12	1400	10	30
13	860	20	30
14	860	10	30

Run Order	**Rotational speed (rpm)**	**Welding time (second)**	**Pressure (bar)**
15	2000	10	30
16	860	10	20
17	860	30	10
18	2000	20	30
19	860	20	20
20	860	20	10
21	1400	30	20
22	2000	10	20
23	1400	20	30
24	2000	20	20
25	2000	30	30
26	860	30	30
27	2000	20	10

To clarify the weldability of the joint, the AA6063-T5 specimen were welded with the method as described in Section 2.2. The ultimate tensile strength, which best represents the ductility and strength of joint welding, was the response of this work. Figure 4 shows the examples of the appearances of weld specimens before and after the tensile test at various parameters. It can be clearly seen that different cracks are subject to different up/down levels of welding conditions. The ultimate tensile strength data from the tensile test was demonstrated in Figure 5. As can be observed, the experimental parameterization caused the results to differ. Therefore, it can be assumed that the changing process parameters affect the contact force and welding temperature.

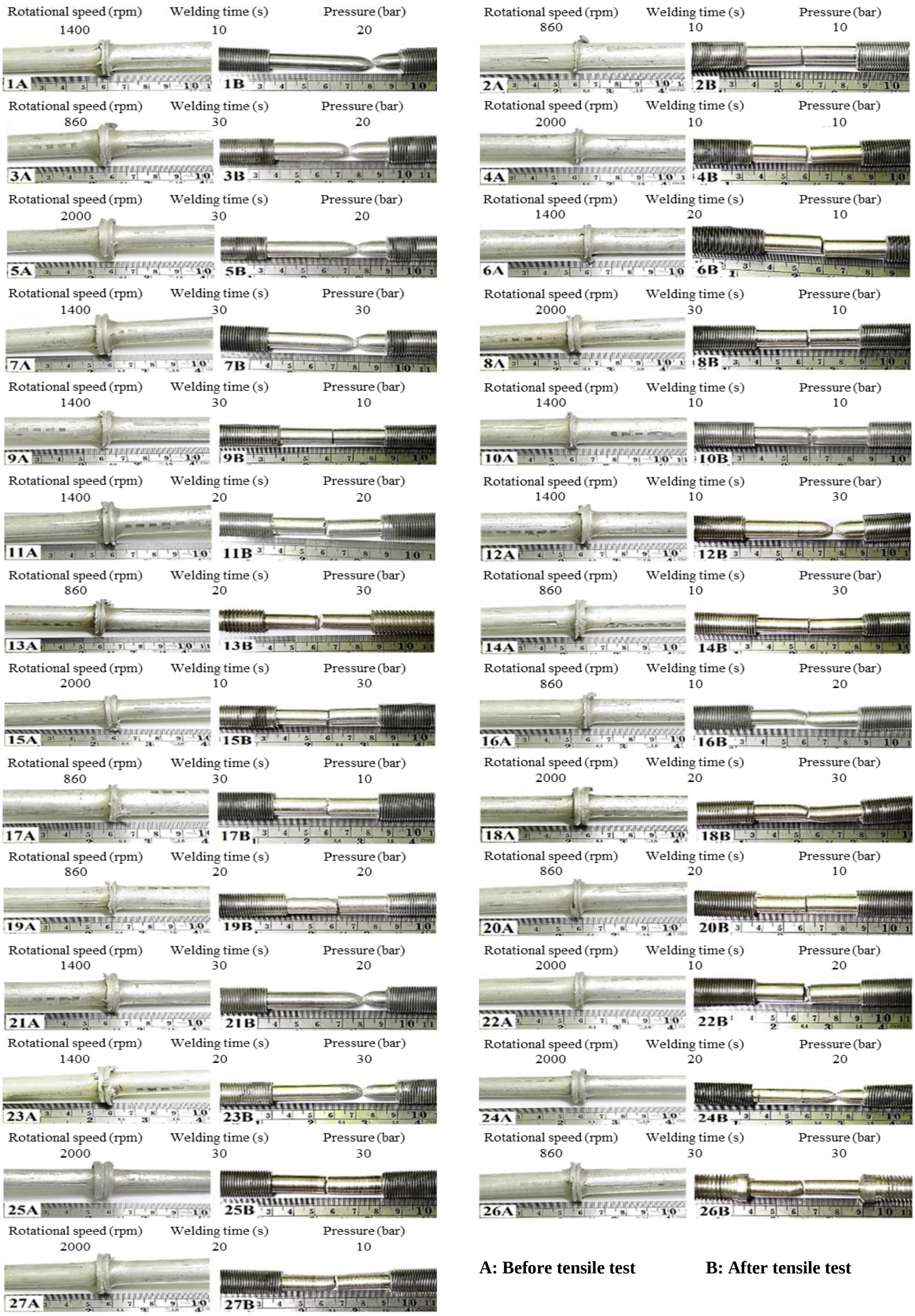

Figure 4. Appearances of weld specimens before and after tensile test at various parameters.

3. Results and discussion

The results obtained from the three-level factorial design of the rotary friction welding experiment were statistically analyzed in three ways: verification of accuracy of the experiment model, analysis of variance and analysis of optimum parameters, all of which were performed using Minitab 16 statistical software.

3.1 Verification of accuracy of experiment model

Verification of suitability and validity of experimental data were a very important step before further analysis of variance. This verification consists of normal distribution, independence and variance stability [20]. The results of the normal distribution verification found that the residual values were linearly distributed and the p-value was 0.998, which was greater than the significance ($\alpha = 0.05$) as shown in Figure 6. It can be clearly accepted that the residual values are normally distributed.

For the verification of data independence, it was found that the residual value distribution had an independent random pattern and that the exact trend could not be estimated as illustrated in Figure 7. Therefore, the residual values were independent of each other. The verification of variance stability based on the residual versus the fitted value showed that the residual variance was approximately the same. Similarly, there were no clear evidence for the tendency of the residual variance data as shown in Figure 8. Thus, it can be estimated that the data has an acceptable level of stability of variance.

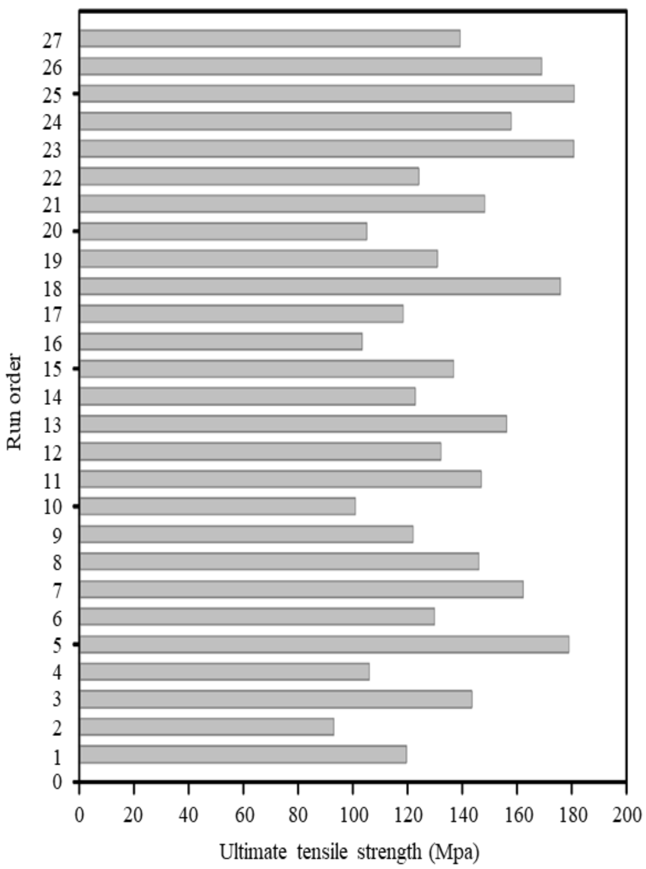

Figure 5. Ultimate tensile strength data from tensile tests.

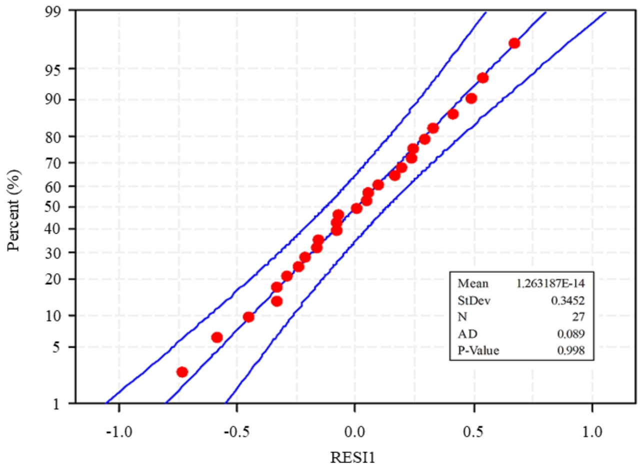

Figure 6. Normal probability plot of residuals.

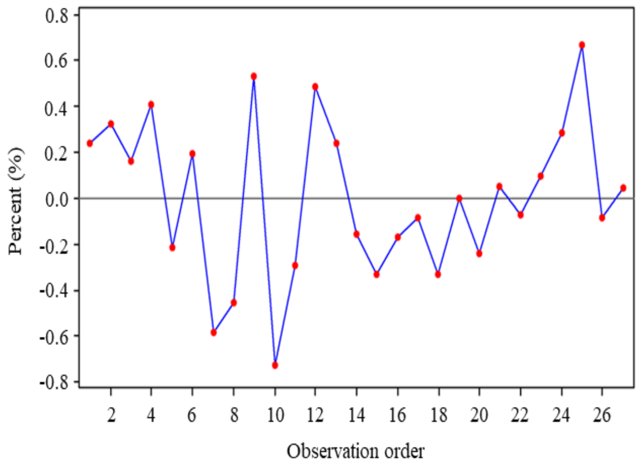

Figure 7. Residuals versus order of observation data.

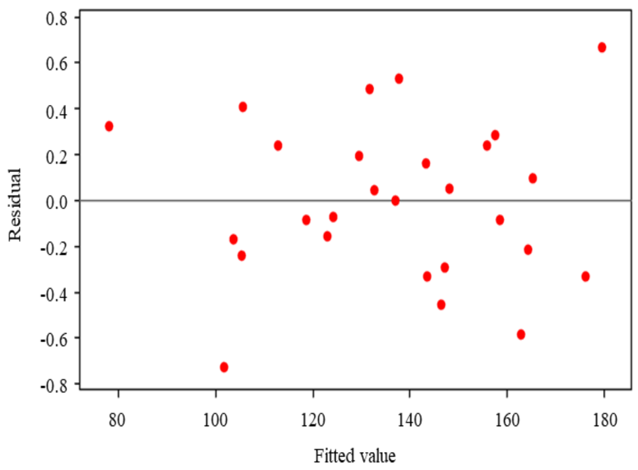

Figure 8. Residuals versus the fitted value.

From the verification procedure mentioned above, it can be concluded that the residual values obtained from the experiments are consistent with the validation principles of the experimental model. Therefore, it can be concluded that the three-level factorial design were an appropriate condition.

3.2 Design constraints

Analysis of variance as shown in Table 4, the rotational speed welding time pressure significantly influenced the ultimate tensile strength, with a p-value less than 0.05. Also, when considering the interaction of factors, it was found that the co-effect of factors was a significant effect on the ultimate tensile strength as well. The coefficient of determination R-square is equal to 99.98 percent. Obviously, in this work, 99.98 percent of the experimental factors were controlled, and only 0.02 percent were uncontrollable factors. This suggests that the variable selection in the frictional welding investigations in this study can be done with reliability. On the other hand, there were certain variables that were not looked at in this study but only had a little impact on the results (0.02%).

3.3 Analysis of optimum parameters

An experiment for determining the optimum condition for the weld strength test was close to the original metal-based, it must be close to 186 MPa. Result analysis with a response optimizer method, it was found that the rotational speed of 2000 rpm, welding time 26.97 sec and pressure 30 bar were determined to be optimal conditions for the rotary friction welding process. At this optimal condition, it has an ultimate tensile strength of 179.148 MPa, which slightly differs from the original metal-based as illustrated in Figure 9. The results of friction welding operations under optimal conditions, as determined by statistical analysis, revealed that friction welding experiments under such conditions produced a weld tensile strength of 180.23 MPa. As a result, there was a 0.6 percent error in the predicted result.

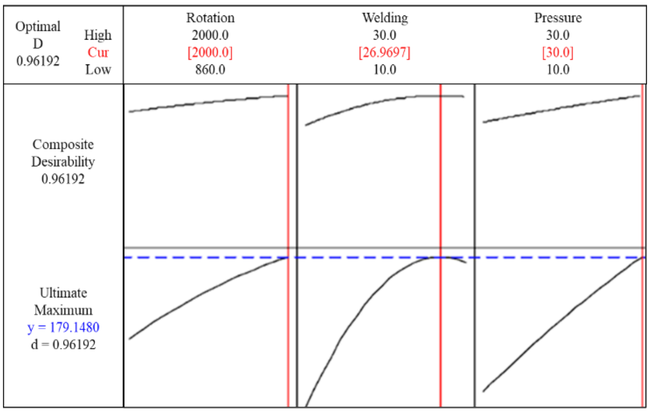

Figure 9. Optimization plot of parameters.

Table 4. Analysis of variance.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotational speed	2	2378.57	2378.57	1189.28	3070.35	0.000
Welding time	2	7244.49	7244.49	3622.24	9351.48	0.000
Pressure	2	6475.41	6475.41	3237.71	8358.72	0.000
Rotational speed*Welding time	4	35.86	35.86	8.97	23.15	0.000
Rotational speed*Pressure	4	213.39	213.39	53.35	137.73	0.000
Welding time*Pressure	4	94.40	94.40	23.60	60.93	0.000
Error	8	3.10	3.10	0.39		
Total	26	16445.22				

S = 0.622370, R-Sq = 99.98%, R-Sq(adj) = 99.94%

4. Conclusions

This paper presents an optimization of rotary friction welding process parameters, namely rotation speed, rotation time, and pressure using a three-level factorial design methodology. The conclusions and analytic results draw in this work are as follows:

(1) The three-level factorial design methodology designed experiments of rotary friction welding on aluminum round bars AA6063-T5 were successfully conducted.

(2) The processing factors were determined using the design of experiment approach. The interaction and effect of the main parameters were highly efficient for similar weld quality to its original metal-based.

(3) Analysis of variance demonstrated that all of the parameters highly affected the ultimate tensile strength of the joint, with a p-value less than 0.05. In addition, the co-effect of factors was a significant effect on the ultimate tensile strength as well.

(4) The optimum welding parameters for the ultimate tensile strength are the rotational speed of 2000 rpm, the welding time of 26.97 sec and pressure of 30 bar, which provides a maximum weld strength of 179.148 MPa.

Optimization of rotary friction welding with limited various solutions could be achieved for the benefit of improving the quality and for reducing production costs. However, the result presented in this work was specific to the study of structural properties of welds at the macro level only. A future research challenge will be to use the electron back scatter diffraction (EBSD) inspection technique to investigate the crystallographic orientation of rotary friction weld joints of ultra-high strength steels (UHSS). In the field of materials engineering, it is a method of analyzing material characteristics at the microstructural level that is gaining popularity. Then use it in the industrial sector to manufacture metal parts.

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