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Optimization Of Process Parameter On Friction Stir Welding Of Aluminium 6061 Using Partial Fraction Method

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Abstract: Friction Stir Welding is a technique resulting in the material producing a low distortion and high joint strength compared to other joining techniques. In this paper, Friction Stir Welding is conducted on Aluminium 6061 using mild steel as there is less research made to obtain the optimum parameter on friction stir welding using conventional milling. In determining the optimum process parameters, the diameter of the cylindrical tool pin, the rotational speed of tools and the traverse speed of the tool tip are the variables. Generating MINITAB software on partial fraction yields analysis on contour plot, surface plots for optimizations and the response optimization data for the parameters. From the conducted experiments, the optimum parameter that has been found is the diameter of the tool pin is 4mm, the rotational speed is 795rpm and the traverse speed is 17mm/min.

Keywords: Friction Stir Welding, Diameter Of Tool Pin, Rotational Speed, Traverse Speed

1. Introduction

Nowadays, there are many techniques for joining two aluminum plates together. The most common technique is MIG welding. By using this technique, one can detect defects occurring due to uneven heating and cooling of the material. This will result in the fatigue strength of a material joint being reduced. It is found that using the base material itself as a medium to join the plate will be the optimum way to reduce the side effects of traditional welding. Friction stir welding (FSW) is a modern technique in conducting welding. As it is a new method, not much research has been made to ensure to have an optimum parameter for this process for aluminum 6061. To solve this, different parameters are needed to be searched to select the most suitable parameter to conduct the friction stir welding using the partial fraction method.

FSW is a joining method that is invented by The Welding Institute (TWI) in 1991 in Cambridge, United Kingdom. There are more than 200 licenses for the application of FSW in the industry by 2007. In summary, FSW occurs when the rotating tool is pressed against the surface of two abutting or overlapping plates. The important component in FSW is the probe (pin) which protrudes from the base of the tool (shoulder) and its length is only marginally less than the thickness of the plate. When the

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tool is plunged to the base and as the plate softened and cannot escape due to the constraint produced by the shoulder, the tool will transverse along the line of the expected joint. The extruded materials formed will be deposited to the retreating side of the tool and formed a solid phase joint behind the tool. This paper discusses optimizing the main parameters of friction stir welding which are the tool geometry, rotational speed, and the traverse speed of the tool.

One of the most important aspects of Friction Stir Welding (FSW) is tool geometry. It's crucial for controlling material flow since it controls the FSW tool's traverse rate. Friction at the shoulder-material contact is a primary source of heat production. The tool shoulder is characterized by shoulder diameter, which can be flat, concave, convex, or scrolling. The Friction Stir Welding (FSW) procedure was used to examine improved tool geometries such as MX Triflute and Whorl pins. Both tools have pins that are formed like a frustum, which displaces less material than a cylindrical tool with the same root diameter. It is made up of numerous different types of tool pins with flutes on the threaded pin. The design characteristics of the improvement tool geometry with flutes can reduce the welding force, allowing for easier melted material flow, aid the downward auguring effect, and enhance the contact between the pin and melted material, this will result in increased heat generation. [1]

Research has been made in 2011 by Arora by conducting friction stir welding using the different diameters of cylindrical shape tool pins of 15mm, 18mm and 21mm [2]. The resulting yield that the diameter of 18mm of the diameter of the tool pin produces the highest yield strength of 130.3MPa. With a thickness of 3mm of aluminum alloy plates, research has been made by using tool pin diameters of 3mm, 4mm, and 5mm [3]. This research has found that increasing the tool pin diameter for a fixed rotational speed tool decreases the fatigue strength of the joint.

In Friction Stir Welding, the rotational speed of the tool plays a crucial role in producing good quality. The best rotation speed and traverse speed of the tool tip must be ranged between 1200 rev/min and 50 to 100 mm/min for a constant offset of 1mm on the welded joint quality. Research made by Barekatain et. al in 2014 has found that rotational speed plays a crucial role in producing a good-quality of welding. High rotating speeds can affect the recrystallization process, which can then affect the Friction Stir Welding (FSW) process. The stressed zone extends as the rotation speed rises, and the highest strain eventually shifts to the advancing side of the joint from the original retreating side. Both strength and elongation improved as spindle speed rose, reaching a peak before dropping at high rotating speeds. The predicted maximum temperatures, on the other hand, are practically identical at all rotational speeds. This can be further explained by two reasons which are the coefficient of friction decreases when a local melt occurs at the joint plate.

In 2014, Suri was experimenting with two distinct types of tool pins: straight thread pins and improved flat pins. The tool's rotating speed was adjusted to 400, 600, 800, 1200, and 1400 rpm, with a constant traverse rate of 30mm/min. According to the results of the experiment, using rotational speeds of 800 and 1200 rpm on straight thread tool pins would give a higher surface finish on the FSW process owing to optimal material softening [4].

2. Experimental setup

Before experimenting, some experimental setups need to be done before continuing the Friction Stir Welding. In the fabrication and welding processes, lathe machines and milling machines are employed

2.1. Material selection

The materials employed for this experiment were selected based on their mechanical characteristics and their suitability for the Friction Stir Welding technique. The Base Material (BM) is made of aluminum A6061. This is because aluminum A6061 has poor weldability for friction stir welding due to its mechanical characteristics. The required dimension for the project will be cut since the material we'll be utilizing has dimensions of 200 x 250 x 3 mm. The base material has the following dimensions: 50 x 50 x 3 mm.

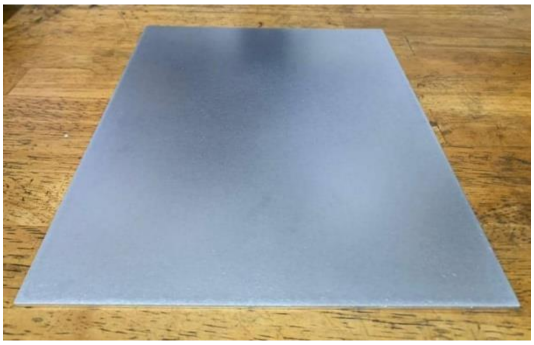

Figure 2.1: Aluminium 6061 plate

2.2. Tool fabrication process

For the Friction Stir Welding tools or known as the tool tip, mild steel was chosen as the material. Mild steel is a suitable combination for conducting the Friction Stir Welding (FSW) with aluminum A6061 as its Base Material (BM) due to the mechanical properties of both the mild steel and the aluminum where the thermal resistance of the mild steel is higher compared to the aluminum alloy 6061. In the fabrication process of the Friction Stir Welding tool, three parts needed to be highlighted which are the body, shoulder, and tool pin. The fabrication process involves the designing of the tool pin profiles that consist of various designs of the tool tip. This experiment uses two design of tool tip design which is straight cylindrical with different diameters of 2mm and 4mm. A conventional lathe machine is used to fabricate the desired tool pin as it has a cylindrical shape. The dimension of the shoulder and the length of the pin is kept the same for all tool tips that are to be fabricated. The diameter of the shoulder is 15mm and the length of the tool pin is 2.8mm.

Table 1: Characteristic of tool pin

Diameter of tool pin (mm)	Material	Height of tool pin (mm)
2	Mild steel	2.8
4	Mild Steel	2.8

As the FSW is to be conducted under a high-speed rotating tool, the possibility of the aluminum plate moving is high. Therefore, a jig is needed to prevent the plate from moving. With the help of a clamp, the plate is unlikely to move even under the pressure of a high-rotating tool.

2.3. Friction stir welding

When conducting the Friction Stir Welding process, the parameters of the tool's rotational speed and its traverse speed need to be determined. Table 2 shows the welding parameters of different diameters of tool tip, rotational speed, and traverse speed.

Table 2: Parameters for the Friction Stir Welding process

Diameter of tool pin (mm)	Traverse speed (mm/min)	Rotational speed (rpm)
2	8.33	795.2
4	16.67	1583.0

2.4. Partial fraction methodology

A partial fraction method with center points and a collection of axial points allow the curvature estimations. Compared to the full fraction method, the partial fraction method has reduced the number of trials that are required for these experiments. The experiment conducted a total of 4 complete partial factorial designs with three factors and two levels. MINITAB software generates the optimization by inputting the rotational speed, traverse speed, and the diameter of tool pin. The levels are divided into High and Low.

Factor	Name	Type	Low	High
A	Diameter of t	Numeric	2	4
B	Rotational Sp	Numeric	795.2	1583
C	Traverse Spe	Numeric	8.33	16.67

Figure 2.2: Factors input in MINITAB

3. Result and discussion

3.1. Friction stir welding

The experiment was conducted in steps which are tool pin production, cutting plate and friction stir welding. In conducting the friction stir welding process, the base material was clamped to ensure there is no movement when conducting the process as shown in figure 3.1.

After the plate is joined in the figure below, it needs to let rest before taking it out as heat is generated

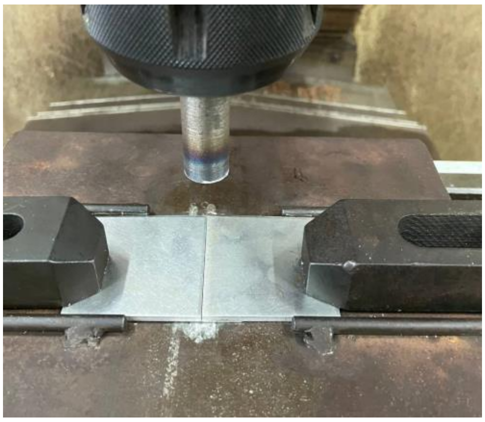

Figure 3.1: Base material is clamped before welding process

when conducting the friction stir welding. From Figure 3.2, the lower left joint plate is designated as the first in the run order which has a parameter of 2mm for the diameter of tool pin, 1583rpm of rotational speed and 8mm/min for the traverse speed, followed by the lower right joint plate as the second run that is conducted with 2mm of diameter tool pin, 795rpm of rotational speed and 17mm/min for traverse speed. The upper right is the third run with 4mm of diameter tool pin, 795rpm of rotational speed and 17mm/min of traverse speed while the fourth run is on the upper left is conducted with a diameter of tool pin is 4mm, the rotational speed is 1583rpm and traverse speed is 17mm/min. Based on the observation that has been made, it was seen that the first and second run produces a clear dissipation on the trailing edge side of the shoulder. For the third and fourth runs, it was observed that there is less dissipation occurred on the trailing edge side of the shoulder. This may be due to the difference between the diameter of tool pin that we used in conducting this friction stir welding

Figure 3.2: Joint plate by friction stir welding with different parameters

3.2. Defects analysis

On the observation of the friction stir welding process, it was found that some defects may affect the result of the objective of this experiment which is optimization of the friction stir welding. The aluminum plate that is joint with different parameters applied has gathered some defects that may be due to the rotational speed of the tool pin when it is too slow or too fast.

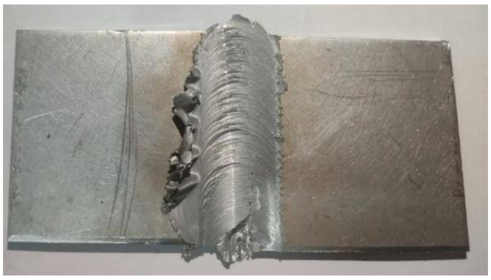

Figure 3.3: Welding defects in friction stir welding

The first defect that was observed is the flash defect. The reason behind this defect is because of the formation of dissipation at the trailing edge side of the shoulder. This is the result of the joint experiencing an elevated temperature of heat due to the rotating tool pin. The heat generated by the welding has softened the material into a severe plastic form. When the material is melted, the pressure that is input by the shoulder led to the dispelling of the excessive amount of flash. The second defect that can be seen in the figure above is the tunnel defect. This defect occurred on the advancing side due to insufficient heat that is given to the material. This may be due to the less time taken when waiting for the plastic formation when plunging the tool pin into the joint. As the process is conducted without observing the formation of plastic the joint does not receive the heat needed and this led to the formation of tunnel defects. This defect can be avoided by increasing the time taken to complete the welding. The traverse speed also needs to be lowered to avoid this defect from occurring.

3.3. Dog bone production

After analyzing the defects that occurred from the welding process, the joint plate is constructed into a dog bone that is in line with the ASTM standard which is ASTM D3039. Figure 3.4 shows the parameters that must be followed to ensure the data on the tensile test is accurate.

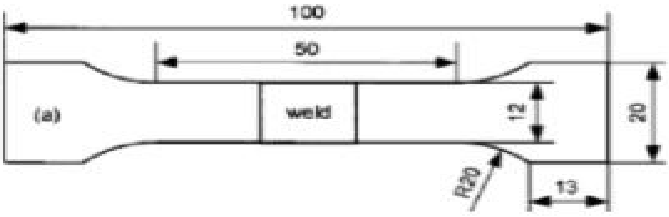

Figure 3.4: Dog bone design from ASTM D3039 requirement

To complete the dog bone production process, CNC Vertical Milling Machine is used to produce the shape of the dog bone. Below is the figure of the process of constructing a dog bone using the machine. Figure 3.6 shows the result of the dog bone production after cleaning and making a grip for the dog bone.

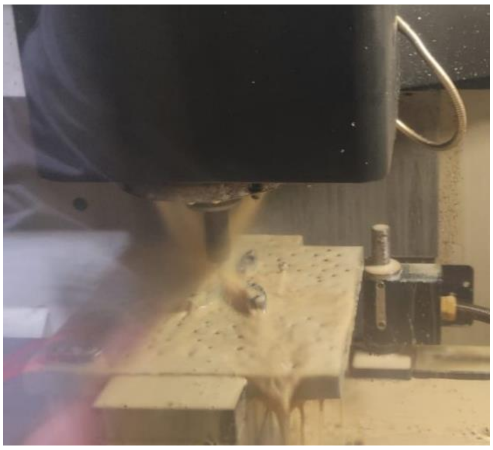

Figure 3.5: Dog bone production in progress by using CNC Vetical Milling Machine

As the dog bone production is completed, the finishing is done by clearing the chipped end of the dog bone and making a grip on both sides for the tensile testing process.

Figure 3.6: End product for dog bone production

3.4. Tensile strength tests

A tensile strength test is conducted to evaluate the value of maximum elongation, force applied, maximum stress, maximum strain, a breaking point of the elongation, breaking point of the force, break point of strain and stress. From here, one can determine which parameter produces the highest tensile strength based on the graph as it will show the maximum stress and the breakpoint stress of the specimen.

Table 3: Data summary on tensile testing

Data	Number of runs			
	1	2	3	4
Maximum elongation (mm)	0.17	0.53	4.43	3.58
Force applied (kN)	3.02	4.12	0.29	0.27
Maximum stress (MPa)	83.76	114.40	123.08	99.38
Maximum Strain (%)	0.33	1.07	0.60	0.55
Elongation breakpoint (mm)	0.17	0.73	0.30	0.67
Force breakpoint (kN)	3.02	3.38	4.43	1.87
Stress breakpoint (Mpa)	83.76	94.03	123.08	51.91
Strain breakpoint (%)	0.33	1.47	0.60	1.33

Based on this data, it was observed that the stress breakpoint is highest at the third run with 123.08MPa. This may show that the parameters that are used in the third may produce the best welding compared to the others as there may be no defects that occurred in the joint plate. Below is the graph of Stress vs Strain that is obtained by conducting the tensile testing for all the runs.

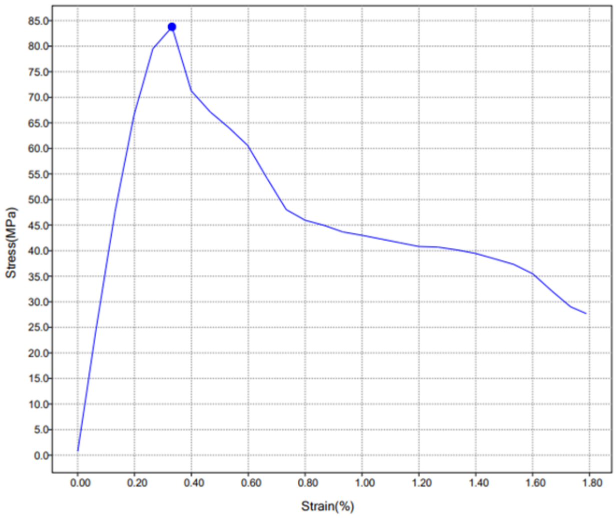

Figure 3.7: Graph of Stress vs Strain for run 1

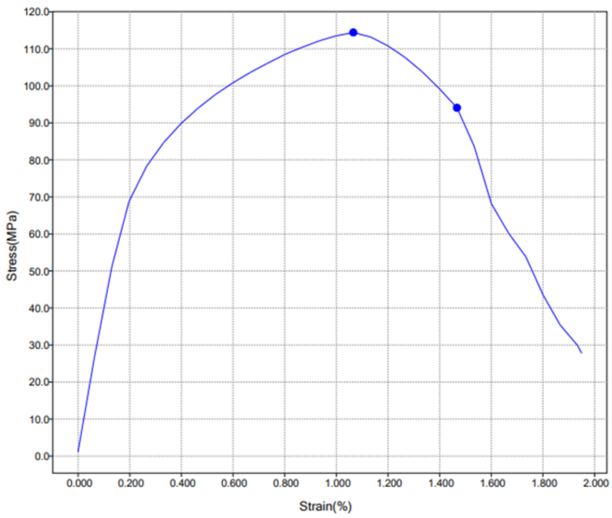

Figure 3.8: Graph of Stress vs Strain for run 2

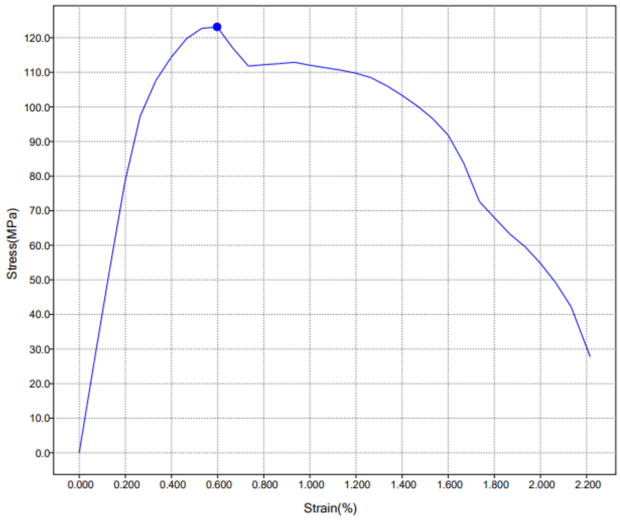

Figure 3.10: Graph of Stress vs Strain for run 3

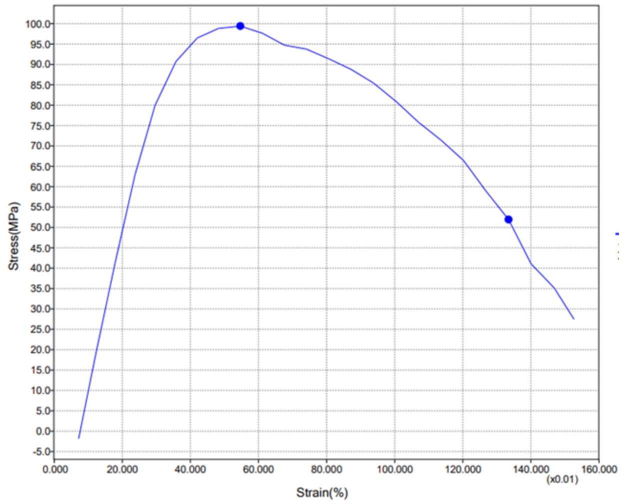

Figure 3.9: Graph of Stress vs Strain for run 4

The ultimate tensile strength can be defined as the force that is required to pull the material to the point where it will break. Based on this, ultimate tensile strength can be gained in the graph of stress vs strain in Figures 3.7, 3.8, 3.9, and 3.10. It is a value at the highest point of the stress in tensile testing that can be gathered. The value of the ultimate tensile strength is shown in the table below.

Table 4: Ultimate tensile strength by runs

Run	Ultimate tensile strength (MPa)
1	83.76
2	114.40
3	123.08
4	99.38

3.5. Optimization using partial fraction

In order to get the optimization on the parameters that has been made in friction stir welding, Minitab software was used to generate which parameters and values are most suitable for friction stir welding. As partial fraction is conducted in MINITAB, the result of analyzing the factorial plot yield contour graphs on parameters and surface plot graph. Response optimization is generated to get the optimum parameter to acquire a high value of tensile strength.

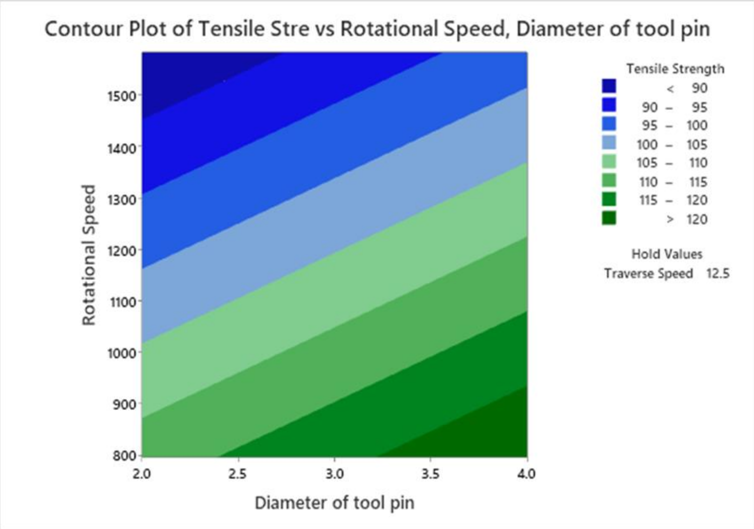

Figure 3.11: Contour Plot of Tensile Stress vs Rotational Speed, Diameter of tool pin

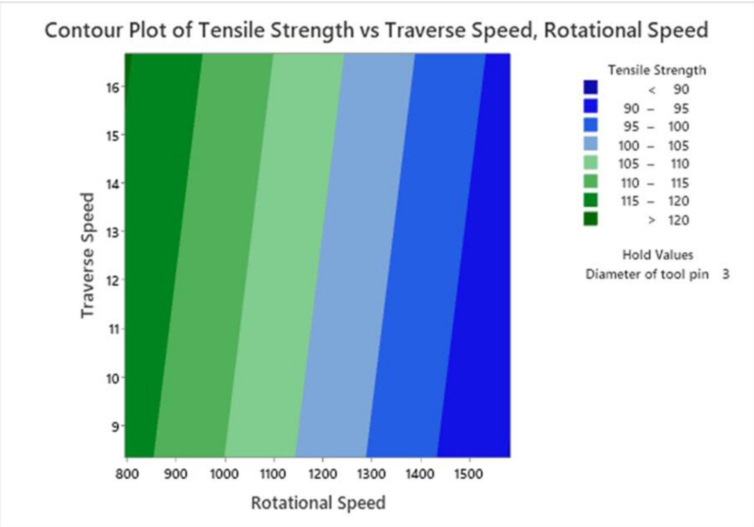

Figure 3.12: Contour Plot of Tensile Strength vs Traverse Speed, Rotational Speed

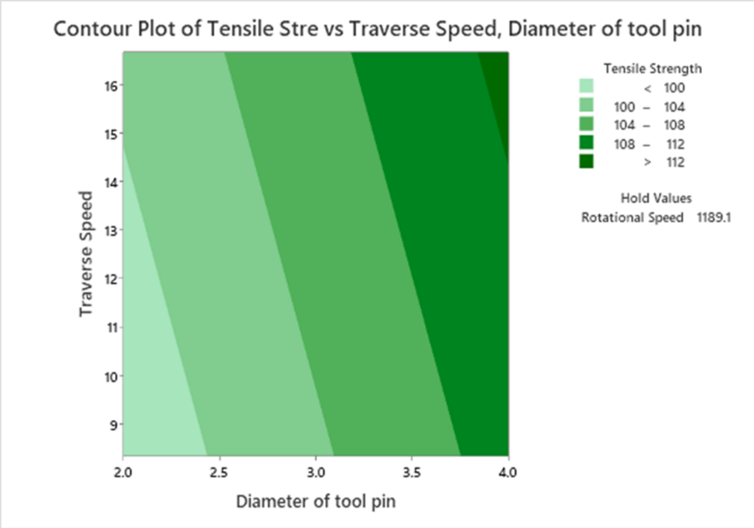

Figure 3.13: Contour Plot of Tensile Stress vs Traverse Speed, Diameter of Tool pin

In Figure 3.11, the contour plot of Tensile Stress vs Rotational Speed, Diameter of the tool pin shows a regression plot. Based on the graph, the optimum condition to get a high value of tensile strength is by having the diameter of the tool pin bigger, and the rotational speed of the tool pin lower. The lower right part of the graph describes that both these parameters will provide a high value of tensile stress with a hold value of the traverse speed is 12.5mm/min. If the hold value is changed, the contour plot of this parameter will be affected. Figure 3.12 shows a contour plot for Tensile Strength vs Traverse Speed, Rotational Speed. As the hold value for the parameter of the diameter of the tool pin is at 3mm, the constructed plot has determined that to achieve high tensile strength is that the traverse speed needs to be sped up more while the rotational speed is slowed down. This may be due to avoiding any plastic formation to be splashed out of the welded joint and creating flash defects. Figure 3.13 provides a contour plot of Tensile Stress vs Traverse Speed, Diameter of the tool pin. From this graph, it is understood that the upper right plot of this graph produces the highest chance of obtaining a high tensile strength. With a hold value of 1189.1rpm for its rotational speed, it was understood that the traverse speed needs to be high, and the diameter of the tool pin need to be bigger.

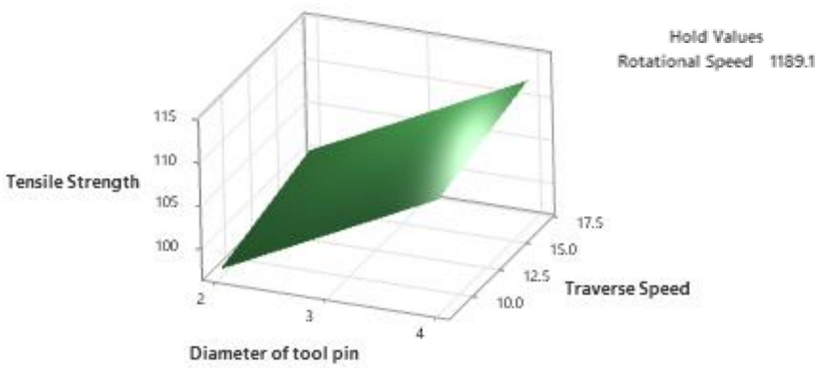

Figure 3.14: Surface Plot of Tensile Strength vs Traverse Speed, Diameter of tool pin

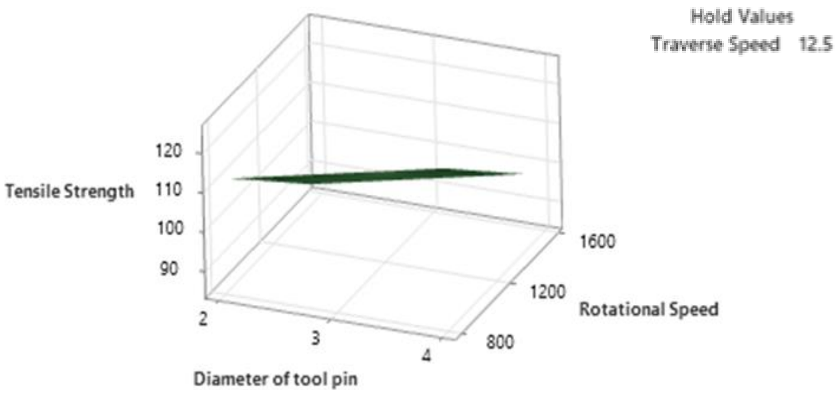

Figure 3.17: Surface Plot of Tensile Strength vs Rotational Speed, Diameter of tool

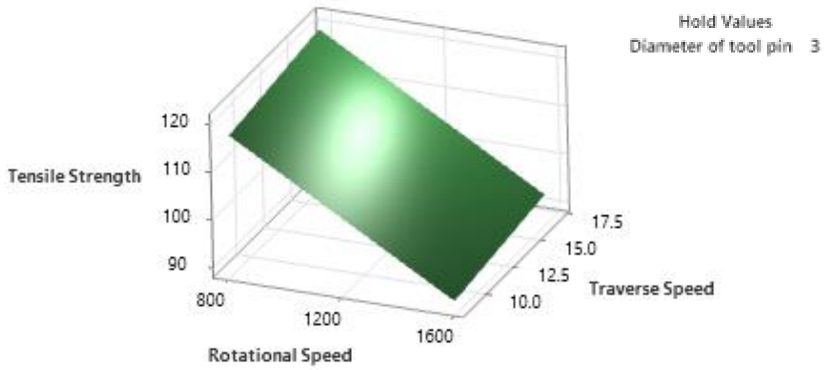

Figure 3.16: Surface Plot of Tensile Strength vs Traverse Speed, Rotational Speed

A surface plot graph is a method to calculate which parameters will yield the highest tensile strength with a parameter being in a constant value. Figure 3.14 provides a graph of the surface plot of Tensile Strength vs Traverse Speed, Rotational Speed with the diameter of the tool pin is hold at 3mm. From this graph, the result shows that to yield a higher tensile strength, the traverse speed needs to be increased and the rotational speed must be slower. Figure 3.15, is a surface plot of Tensile Strength vs Rotational Speed, the Diameter of the tool pin and the hold value is the traverse speed with 12.5mm/min. This graph shows that a diameter of the tool pin of 4mm with a rotational speed of 800rpm produces the highest tensile strength. Figure 3.17 shows a surface plot of tensile strength vs Traverse Speed, Diameter of the tool pin with a constant value of 1189.1rpm. From this graph, as the traverse speed and the diameter of the tool pin increase, the value of tensile strength will increase as well.

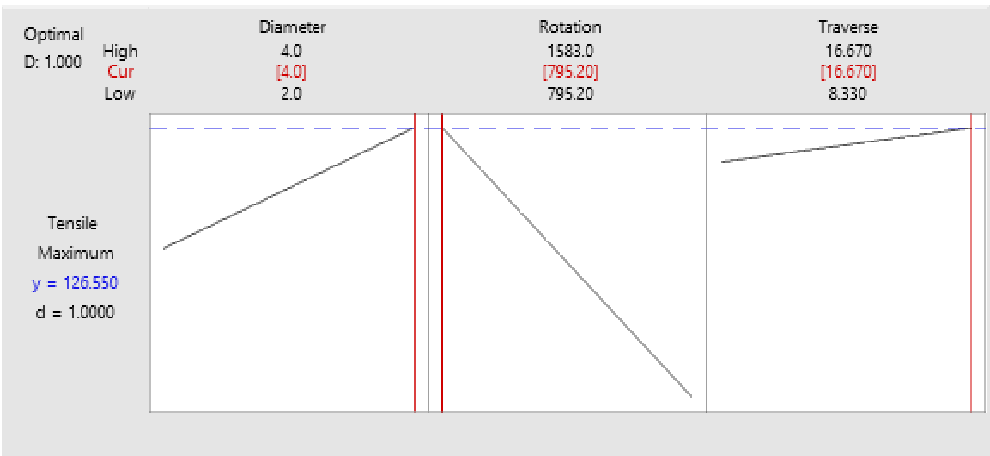

Figure 3.15: Response Optimization

To gain an optimization on friction stir welding parameters, a surface response optimization is generated. This response optimization is based on achieving the highest value of the set parameter which is tensile strength. Figure 3.16 shows the result of optimization using each parameter. Based on these three graphs, the optimum parameter that is suitable to get a high tensile strength is by having a larger diameter of the tool pin. Whereas the traverse time needed to complete the welding must be quicker as the value chosen is on the high side. For the rotational speed, response optimization concluded that it is needed to have a lower rotational speed to achieve a higher tensile strength in the joint. Based on the methodology of partial fraction in optimizing the set parameters, the data has shown that to optimize the welding parameters, one will need to use a diameter of tool pin of 4mm, a rotational speed of 795rpm and a traverse speed of 17mm/min.

4. Conclusion

The study have achieved the objectives of determining the optimum process parameters of the friction stir welding on aluminum 6061 using the partial fraction method. The aluminum plate has a thickness of 3mm with a size of 200mm x 250mm. The aluminum 6061 plates were cut into smaller pieces with a size of 50mm x 50mm and welded together using mild steel as its tool. The welded part has been observed and defects have been identified to be improved in further studies. As the welding has been completed, there are some good welded joints and some bad welded joints. The pressure needed to conduct the friction stir welding must be identified to avoid the appearance of defects. Defects such as flash defects and tunnel defects are observed and discussed so that there will be no defects that will affect the results of the tensile testing

The optimization of friction stir welding by using the partial fraction method is conducted by analyzing a fraction of the runs in a full factorial methodology. This has resulted in some of the main effects being confounded and cannot be separated. Even though some of the main effects are confounded, the study have achieved the data on the optimum parameters for the friction stir welding parameters that have been set. The optimum parameter that has been found is the diameter of the tool pin is 4mm, the rotational speed is 795rpm and the traverse speed is 17mm/min.

Friction stir welding experimentation can be done on a conventional milling machine. As it is a conventional milling machine, it is a requirement to understand the principles of the milling machine and check if there is any error in its accuracy. This will help future studies in predicting the exact plunge length that is needed so that it will not penetrate the jig itself. When conducting friction stir welding, the plunge of the tool pin must be observed every time to ensure that plastic formation appears before moving the tool pin. When the tool pin is plunged, it is very important to ensure that the time taken for the plastic formation and the movement of the tool pin is short to avoid any flash defects and tunnel defects. For future studies when conducting partial fraction methodology, it is recommended that two input replicates is used so that the data is more accurate even though it is using the same parameters.

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