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Effect of Friction Welding on Tensile Strength of Polymethyl Methacrylate (PMMA) by Computerized Numerical Control Machine

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Abstract

The objective of this research is to investigate the effect of joining parameters from friction welding process of polymethyl methacrylate on the mechanical properties. Friction welding used lathe computer numerical control machine of applied for welding. Friction welding used different rotation speed such as 600, 1000, 1400, and 1800 rpm; burn of length was 2.2 and 3.2 mm and welding time is constant at 30 seconds. From the investigation, the rotation speed and burn of length parameter influence mechanical properties. The lower rotation speed provides the higher tensile strength. The results showed that the condition with rotation speed at 600 rpm, burn of length at 3.2 mm, and welding time at 30 seconds provides the maximum average tensile strength of 18.11 MPa. In addition, the faster rotation speed causes the lower tensile strength. On the other hand, an increase of burn of length led to higher tensile strength.

Keywords : *Friction welding, Polymethyl Methacrylate, Computerized Numerical Control Machine*

1. Introduction

Polymethyl-methacrylate (PMMA) is modern thermoplastic materials used for engineering applications in automotive industry, such as automobile tail lights. PMMA has good mechanical strength, light weight, acceptable chemical resistance, and extremely good weather resistance of ten substituted for glass (a denser material). Furthermore, PMMA is good transparent and toughness. Although plastics were used in automotive industry as larger or complex parts, these usually required joining technologies, such as bolts or welding. In the last decade, many researchers have tried to improve the present processes and developed many new polymer joining techniques (1). However, generally, welding technology for plastic materials are still difficult to be welded and do not have varieties of process. Friction welding is classified by the American Welding Society (AWS)(2) as a solid-state joining technique generally used for metal or other materials of cylindrical shape, which can be used to join a number of similar and dissimilar metals, and previously has been successful for friction welding (FW) of aluminums (3), Steels (4, 5), titanium (6) and others.

The advantages of FW are high weld quality, non-consumable simplicity, and welding remarkably simple. FW consists of parameters, such as friction pressure, friction time, upset pressure, upset time, temperature measurement, burn of length, weld time, and rotational speed (7). The main concept for FW is material plastic deformation which was generated from heat during the process. Localized heating softens the weld zone and the combination of the weld zone and translation results in producing a welded joint in solid-state. Moreover, note that the FW used in aeronautical, automobile, submarine, and heavy industries (8). However, parameters play a central role during joining and plastic materials are particularly suitable for this technique. Especially, rotation speeds and burn of length are the most important parameters in this process of joining. Recently, some researchers have studied the application of FW to thermoplastics but obtaining good joints is a very hard task, which is a challenge (9, 10).

In the present work, the authors studied FW of PMMA polymer materials with a computerized numerical control machine; the study was performed by changing the main process parameters, such as rotation speed and burn of length. After FW, studies of the characteristics of samples were observed in Macro-Microstructures in welded zone, tensile strength, and fracture surface respectively.

2. Materials and methods

2.1 Materials

The material for experiments is cast plagued PMMA (Acrylic 8H polymer) and the classification for its commercial trademark is PMMA0132V1. In this work, they were formed in cylindrical shape with dimensions of 20 mm in diameter and 70 mm in length. This PMMA grade, along with good dimensional stability and excellent weather and UV resistance, offers a tensile strength of 78 MPa, an elongation around 6-8 percent, and a softening point at 108°C. Before FW, sample preparation was carried out by turning surfaces at 450 rpm with lathe machine and the samples were welded together as a butt joint.

2.2 Methods

In this experimental study, FW used lathe computer numerical control machine (CNC) which was designed by modifying used because of its stability and precision. The spindle was driven by an asynchronous servomotor with maximum rotation speed at 3000 rounds per minute. Axial forces were controlled by a hydraulic servo valve. Steps of how this FW machine works are shown in the (Figure 1).

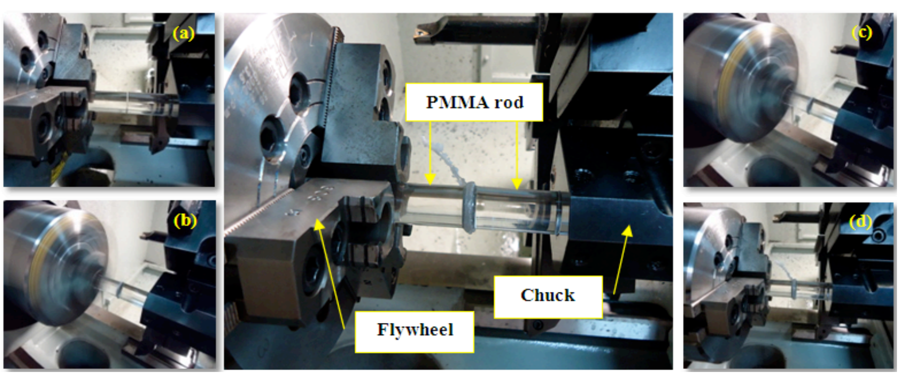


Figure 1. Illustration of the FW process for PMMA.

Samples were taken to the chuck on both sides, and then adjusted to the center position (Figure 1a). Next, the contact surface began to rotate in the clockwise direction generating frictional heat (Figure 1b). Over time, the temperature increased and a volume of softened/molten polymer was created because higher rotation speed can increase both temperature of the samples and the amount of softened/molten polymer. The samples were pressed together and the heat was generated on the welding area. This resulted in changes to the physical characteristics and chemical properties (Figure 1c); some of the material was pushed out become flash. By the end of the welding process, rotation speed was stopped along with the cooling of the samples, which can shrink the samples (Figure 1d). The welding parameters were rotation speed at 600, 1000, 1400, and 1800 rpm, burn of length at 2.2 and 3.2 mm, welding time was constantly at 30 seconds, and feeding rate at 5 mm per minute. The welding parameters are shown in the (Table 1).

Table 1. Welding parameters of the FW process for PMMA.

Number of Experiments	Parameter		
	Rotational Speed (rpm)	Burn of Length (mm)	Weld Time (second)
1	600	2.2	30
2		3.2	
3	1000	2.2	
4		3.2	
5	1400	2.2	
6		3.2	
7	1800	2.2	
8		3.2	

2.3 Tensile Test

After FW, all samples were measured their tensile strength in welded areas. ASTM D638-02 standard was used for sample preparation. The tests were performed at room temperature, using a Testomatic machine with cross-head speed at 5 mm/min.

2.4 Microstructure Analysis

Some of the samples were taken to determine the fracture surface carried out using a light optical microscope (Reich, model: FMA037), and scanning electron microscopy (SEM)(FEI-Quanta, Japan; model: 400), allocated in the Scientific Equipment Center, Prince of Songkla University.

3. Results and discussion

For this study, both best and worst conditions were evaluated in tensile properties and fracture surface were examined. From experiments, each variable of conditions generated similar results. However, the combination of different variables provided different mechanical properties in the welded samples. After selecting a perfect FW condition which provides maximum tensile strength and samples, these good results were obtained by using a rotation speed at 600 rpm, the burn of length for 3.2 mm, and welding time for 30 seconds.

3.1 Characteristics of Samples after FW

Figure 2. shows the photography of samples in all conditions. As you can see, the samples were completely formed and had no defect in all conditions. After FW, physical characteristics in welded zone were changed to be flash (appearance white opaque). Since the heat input made the material soften, a flash was flown out of the welded area. Figure 2. (a, b, c, d) shows the burn of length at 2.2 mm and rotation speed at 600, 1000, 1400 and 1800 rpm respectively, It shows that the welding thermal causes a flash. However, noticed that rotation speed in the range between 600 and 1400 rpm a high volume is caused by heat while welding imperfections shown in the Figure 2. (a, b, c). On the contrary, when rotation speed was increased to 1800 rpm, it was found that high heat input led to texture material softening, which was causing the decrease of flash shown in the Figure 2. (d). Likewise, when the rotation speed is in the range between 600 and 1400 rpm and burn of length at 3.2 mm, it was found that samples were born with a lot of flash after welding as shown in the Figure 2. (e, f, g). This caused by lower rotation speed; however, at higher rotation speed at 1800 rpm, it found that plastic was completely melted with higher melting temperature shown in the Figure 2. (h).

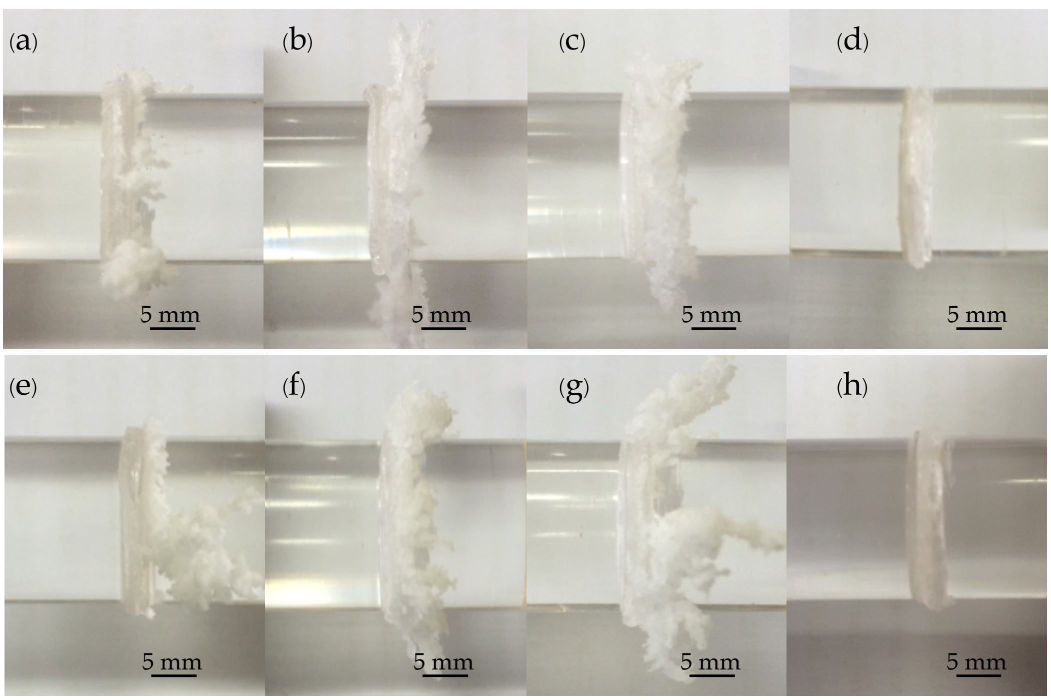


Figure 2. Sample morphology of burn of length 2.2 mm (a) 600 rpm, (b) 1000 rpm, (c) 1400 rpm, (d) 1800 rpm and burn of length 3.2 mm (e) 600 rpm, (f) 1000 rpm, (g) 1400 rpm, (h) 1800 rpm.

However, an increase of burn of length from 2.2 to 3.2 mm resulted many flashes because higher burn of length led the material push away from the seam in the welded zone during FW. Not only burn of length will influence the presence of the flash, but also increasing burn of length will affect the total length of sample after FW. Moreover, feed rate have important during the joining process due to can plastic deformation. However, in this research shows that can be welding of plastic materials and joints better compatibility. FW process for PMMA it seems appropriate for commercial ventures.

3.2 Macro-Microstructures in Welded Zone

Figure 3. shows the macro-microstructure as cross-section photography in welded zone with rotation speed at 600 rpm, burn of length at 3.2 mm, and welding time for 30 seconds. The results showed that the changes of welded zone (WZ) structure which came from the heat in welding within the range from 92^{o}C to 102^{o}C, and physical welded zone appeared to be white opaque unlike the original transparence. The heat generated during welding caused molecular chains to be separated. This will easily allow flash to be happened when higher compression forces are applied. However, PMMA is a plastic material with brittle properties when it was welded resulting in cracks in the welded zone. The Figure 3 (a) shows microstructures at the center of the welded zone (Position A), taken at 2500X by SEM. It found that microstructures in welded zone changes due to the effects of heat makes molecules were destroyed lead to coarse structures when compared to the original structure, which shows that the original structure is smooth structure shown in the Figure 3 (a) (Position C). However, the welded zone in position A cracks located the center of the sample was found because friction temperature at the center is less than surrounded regions (11). In addition, a void was found due to rapid shrinking of the material and the air was trapped inside. Likewise, plastic flow of materials was partially flash and formed as coarse structures similar to the welded zone shown in the Figure 3 (b) (Position B). It was also found that coarse structures are less transparent than smooth structures are.

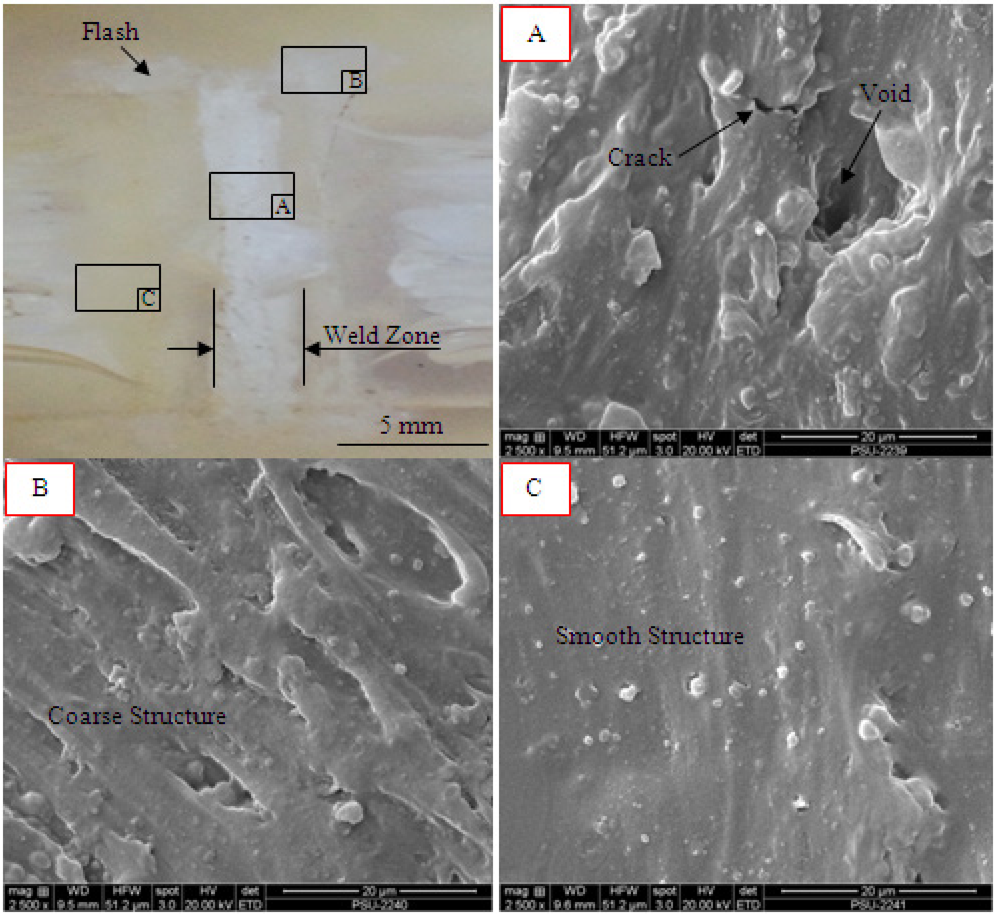
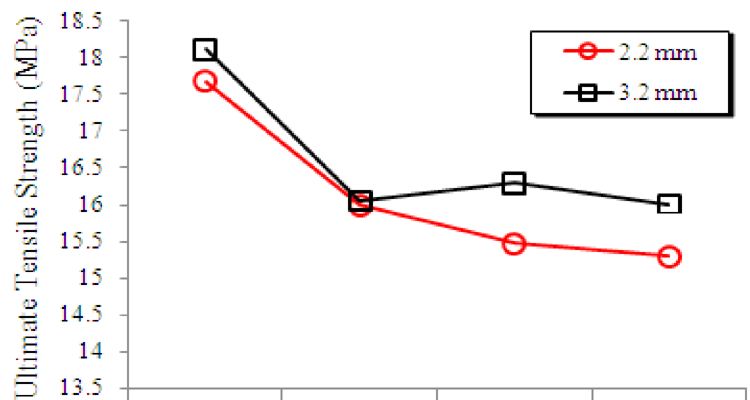


Figure 3. Photography in welded zone of rotation speed at 600 rpm and burn of length at 3.2 mm.

3.3 Influence of Rotation Speed for Tensile Strength

The result of tensile strength of joints welded at different welding conditions shown in the Figure 4. From the study, the higher rotation speed led to a lower tensile strength because higher rotation speed can increase plastic deformation and voids easily. Which PMMA receives high heat while welding, after welding samples are brittle. The rotation speed at 1400 and 1800 rpm has average tensile strength value of 15.47 and 15.29 MPa respectively. In addition, decreased rotation speed from 1000 to 600 rpm resulted increasing tensile strength due to the lower heat input during welding. The maximum tensile strength at rotation speed of 600 rpm, burn of length at 3.2 mm, and welding time at 30 seconds was 18.13 MPa. In addition, for rotation speed of 1000 rpm, it has tensile strength value of 16.05 MPa respectively. However, tensile strength of samples in all conditions were lower when compared with 78 MPa tensile strength value of PMMA base. That dependent bonded zone and heat input makes structure of welded zone reach recrystallizing temperature. During recrystallizing temperature, there will be pores because of the insertion of oxygen during FW. It is noteworthy that burn of length at 3.2 mm provided higher tensile strength than burn of length at 2.2 mm due to a higher density at the interface. However, at very high burn of length, a flash can be observed and samples of welding were shortened. Besides, tensile strength for FW of PMMA directly promoted quantity of the voids.



	600	1000	1400	1800
2.2 mm	17.68	15.99	15.47	15.29
3.2 mm	18.11	16.05	16.29	16.00

Rotation Speed (rpm)

Figure 4. Tensile strength of joint for FW of PMMA.

3.4 Fracture Surface in Welded Zone

Figure 5. shows the tensile fracture surface morphologies of welded PMMA from both rotating side and stationary side at rotation speed 600 rpm, at burn of length 3.2 mm and weld time at 30 seconds which was taken by SEM at 7X magnifying power. The results showed that the fracture surface morphologies of welded PMMA can be divided into three zones, such as (1) The central zone (Fud), which is a "worn-out surface" (2) The middle section (Fpd), which is a partly plasticized zone (3) The peripheral zone (Fpl), which is a "rippling zone" (11). It is noteworthy that the Fud area is large, which is caused less heat from friction However, larger Fud areas affect the strength of the material because it is an area that is not bonded together very well. Meanwhile, the heat from Fpd areas directly came from the increasing friction due to the remoteness of rotation away from the center which led to increase adhesion. Fpl areas mostly received the heat from the friction between the surfaces of both material pieces. Thereby, high heating that occurred during welding caused plasticized pile-up as well. However, it can be seen that large quantities of air bubbles from rotating side occurred after welding shown in the Figure 5 (a) due to air infiltration during the welding process. This incident usually happened when the rapid cooling plastic turn confined air to air bubbles. We also found that air bubbles in Fpd areas was larger than Fpl areas shown in the Figure 5 (b, c). Moreover, more air bubbles distribution of Fpd was observed in larger area than air

bubbles distribution of Fpl especially around the edge of the samples. This resulted from the trapped air that coming out of Fpl faster than the Fpd areas. However, the increasing volume of the air bubbles led to a decrease in mechanical properties.

On the contrary, in the Figure 6, it shows the tensile fracture surface morphologies from both rotating side and stationary side by SEM taken at 7X of welded PMMA with rotation speed 1800 rpm, burn of length 2.2 mm, and welding time at 30 seconds. We also found that higher rotation speeds can cause the higher plasticity leading to larger voids. Figure 6 (a, b) shows the voids from rotation side size about 1.8-2.3 mm wide and about 2.5-3.1 mm long, which these large voids distributed across the surface of joints and this weakens mechanical properties. However another reason that reduces the mechanical properties is that molecular chains are being destroyed. Friction force makes broken molecular chains from stationary side (as mentioned in (11)) and oriented in the same direction of rotation shown in the Figure 6(c). Likewise, higher heat during welding reduced Fud areas, but made Fpd areas wider. The size of Fpl areas is similar to the condition with rotation speed at 600 rpm. In addition, high rotation speed is not a major cause of plasticized pile-up. Therefore, the high tensile strength directly caused by compression forces, not the rotation speed. In contrast, at 1800 rpm, the amount of air bubbles were observed because high heat from rotation turns plastic into more liquid stage which allows more air to be trapped inside. Then, its molecular chains are also destroyed by frication forces (11).

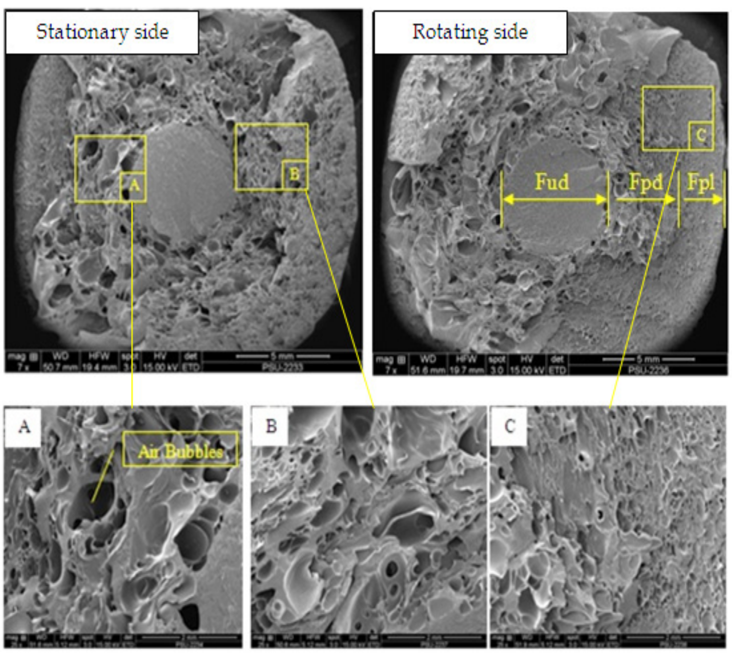


Figure 5. SEM tensile fracture surface morphologies from both rotating side and stationary side for 600 rpm/3.2 mm.

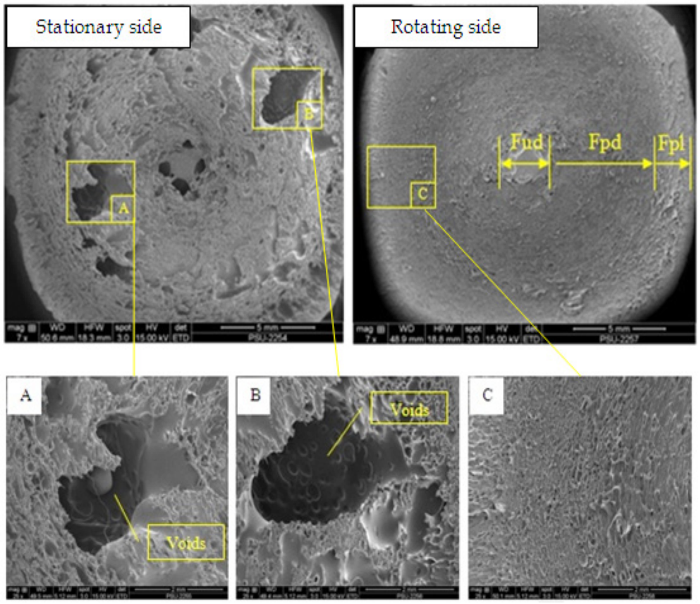


Figure 6. SEM tensile fracture surface morphologies from both rotating side and stationary side for 1800 rpm/2.2 mm.

3.5 Statistical analysis

In the tensile strength process of polymethyl methacrylate, Minitab R.16 software was used for design and analysis by identifying the experimental orders and the General Full Factorial Design in 2 factors, comprised of 4 and 2 levels for each factor, repeated 3 times; thus, the number of experiments was 24 runs as indicated in Table 2.

Table 2. Sequence of the General Full Factorial Design by repeated 3 times.

StdOrder	RunOrder	Factor 1: Rotation Speed (x_1)	Factor 2: Burn of length (x_2)	Tensile strength
9	1	600	2.2	19.193
4	2	1000	3.2	15.390
2	3	600	3.2	18.238
13	4	1400	2.2	16.283
23	5	1800	2.2	15.297
6	6	1400	3.2	16.334
8	7	1800	3.2	14.711
19	8	1000	2.2	16.356
1	9	600	2.2	16.175
3	10	1000	2.2	15.623
11	11	1000	2.2	16.004
14	12	1400	3.2	16.249
10	13	600	3.2	17.979

Table 2. Sequence of the General Full Factorial Design by repeated 3 times. (Continue).

StdOrder	RunOrder	Factor 1: Rotation Speed (x_1)	Factor 2: Burn of length (x_2)	Tensile strength
5	14	1400	2.2	14.647
24	15	1800	3.2	17.297
15	16	1800	2.2	15.886
21	17	1400	2.2	15.488
18	18	600	3.2	18.121
12	19	1000	3.2	16.706
20	20	1000	3.2	16.042
17	21	600	2.2	17.658
22	22	1400	3.2	16.279
7	23	1800	2.2	14.700
16	24	1800	3.2	19.954

Analysis of variance was the investigation of variance sources of the model. From analysis of variance of tensile strength value at 0.05 significant level in Table 3, it was found that p-value of a main effect term was 0.030 less than specified significant level, indicating

Table 3. Analysis of Variance for Tensile strength, using Adjusted SS for Tests.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotation Speed	3	15.554	15.554	5.185	3.86	0.030
Burn of length	1	4.158	4.158	4.158	3.09	0.098
Rotation Speed*Burn of length	3	3.287	3.287	1.096	0.81	0.504
Error	16	21.514	21.514	1.345		
Total	23	44.514				

The optimal factor level was determined to obtain maximum tensile strength value under the condition of this particular experiment and explained by equation (1)

$$y = f(x_1, x_2) \quad (1)$$

In which the tensile strength value (y) was the function of rotation speed (x_1) and burn of length (x_2)

The predictive model was constructed by taking the factor values from analysis of coefficient of regression equation of tensile strength in Table 3 rewritten to be a form of equation (2)

Tensile strength = 18.0 - 0.00122 Rotation Speed (2)

4. Conclusion

In the study, FW of PMMA application of used lathe computer numerical control machine under the different rotation speeds, burn of length and weld time was investigated, Can be seen that the choice of these parameters is important because affects the mechanical properties of the sample. Heat input results recrystallization of the welding zone and molecular chains are being destroyed by friction force making brittle. The optimum condition is rotation speed at 600 rpm, burn of length at 3.2 mm, and welding time at 30 seconds, which can generate tensile strength at 18.11 MPa. But, rotation speed at 1800 rpm, burn of length at 2.2 mm, and welding time at 30 seconds can provide tensile strength at 15.29 MPa. In addition, burn of length at 3.2 mm can create higher tensile strength than burn of length at 2.2 mm. However, an excellent tensile strength results from the amount of air bubbles or voids.

5. Acknowledgement

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