# A Hybrid Thermal Assisted Friction Stir Welding Approach for PMMA Sheets

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**Abstract**
The widespread application of thermoplastic polymers in different aspects of industries has motivated researchers and companies to improve and upgrade their forming, joining and assembling processes to overcome their limitations. One of the newest joining methods of thermoplastics is friction stir welding which is based on frictional heat generated through contact between a rotating tool and the workpiece. A hybrid thermal assisted friction stir welding approach was proposed in this study for two Poly methyl methacrylate sheets. In this method, the stationary shoe was heated up to the specified temperature and then the FSW tool was gradually plunged toward the clamped sheets. The effects of different process parameters such as rotational and traverse speeds and the heater temperature on the mechanical properties of the joints were studied. Results showed that applying the optimum rotational speeds of 1600 rpm and highest traverse speeds of 12.5 mm/min with the stationary shoe heats up to 70% of base polymer melting temperature which leads to the highest joint performance with strength equal to 95% of PMMA strength.

**Keywords**
Thermoplastic Polymer, Poly Methyl Methacrylate, Thermal Assisted Friction Stir Welding

## 1. Introduction

It is necessary to join the same or different plastic products or plastic part and metal when the finished assembly was too complex or large, or when different materials must be used in the assembling process [1, 2]. Welding is frequently used for joining the thermoplastics, in which the part surfaces were melted, allowing macromolecular chains to diffuse into the opposite specimen at the weld interface [3]. Differences in metallurgical and mechanical properties of different materials made their welding difficult in any welding techniques [4].Various welding methods, such as vibration welding [4], laser welding [5], friction welding [6] and friction stir spot welding (FSSW) [7] are known to be effective in different areas of industry. As a relatively new technique, FSW-invented in The Welding Institute (TWI) in 1991-is introduced as an efficient way of joining materials [8-11].

## 2. Background

Recently, some researchers have studied the application of FSW on the thermoplastics polymers. Mendes et al. [12] investigated the effects of rotational and traverse speeds, and the axial force on the FSW of acrylonitrile butadiene styrene (ABS). Hosein et al. [1] investigated the effects of friction stir welding process parameters on the weld quality and creep properties of welded polyethylene (PE) sheets. The results showed that the creep resistance of the welded samples reaches to the base material resistance. The stress-strain behavior of the welded joint was also modeled using mathematical methods. Rezaee et al. [13] studied investigation on the effects of tool geometry on the microstructure and the mechanical properties of dissimilar friction stir welded polyethylene and polypropylene sheets. The results showed that the utilizing the tool with threaded cylindrical pin provides the better mechanical properties for the welded joints versus the tools with squared, triangle and straight cylindrical pin shapes, respectively. Arici and Sinmaz [14] studied the effect of double passes of the tool on FSW of polyethylene. Double passes allowed them to increase the joint mechanical properties.

## 2. Experimental Procedures

### *2.1 Material*

In this study, the PMMA sheet was used as the base material. Rectangular plates of PMMA sheets with dimensions of 160 × 60 $mm^2$ and thickness of 8 mm were used in this study [13]. PMMA is an economical, versatile general-purpose material. PMMA has high mechanical strength, high Young's modulus and low elongation at break. It is one of the hardest thermoplastics and is also highly scratch resistant [15]. The summary of the physical properties of PMMA is presented in Table 1.

Table1. The physical properties of PMMA polymers

| Material | Tensile Strength [MPa] | Durometer Hardness [shore D] | Melting Temperature [$^0$C] | Elongation [%] | Density [g/cm$^3$] |
|---|---|---|---|---|---|
| Poly methyl methacrylate (PMMA) | 80 | 79 | 160 | 2 | 1.18 |

### *2.2 Tool Design*

The designed tool in the present work was consisted of three main parts: a cylindrical rotating pin, a stationary shoulder and a heating system. The photograph of the employed FSW tool is shown in Figure 1.

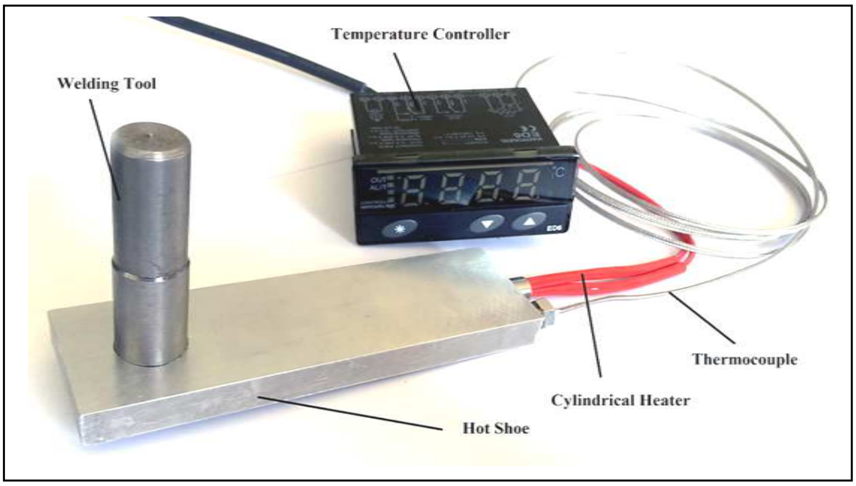


Figure1. Photograph of the designed friction stir welding tool

As it can be seen in this Figure, the tool pin is inserted into the stationary shoulder with a heater, which is equipped with a close-loop thermo controller. Through an indicator, the approximate temperature of the weld zone was presented using a thermal potentiometer. A thrust bearing separated the shoulder from the tool to hold it stationary relative to the tool during welding. The tool was made from H13 hot-working steel, the shoulder was from 7075 aluminum alloy owing to its high thermal conductivity and strength. The stationary shoulder's surface was coated with PTFE (Teflon) in order to prevent the stick phenomenon that may occur between the hot aluminum and the polymer surfaces. The tool and shoulder dimensions are illustrated in Figure 2.

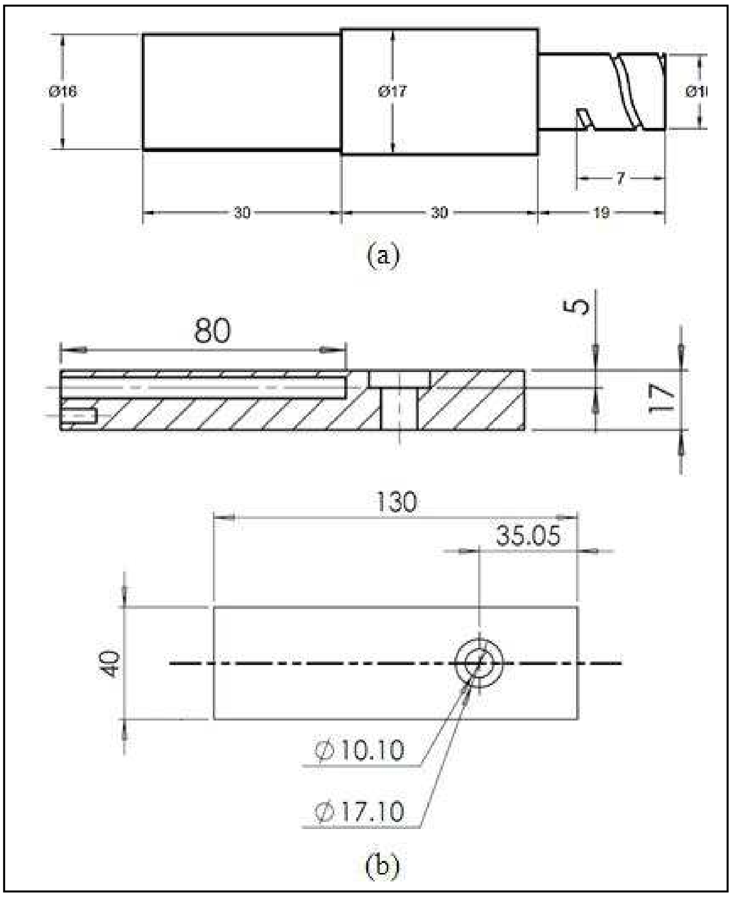


Figure2. Drawings of the designed FSW tool: (a) pin and (b) shoulder (shoe)

In this study, during the friction stir welding of all samples, the tool, rotating pin was positioned at the interface of the plates with no offset. The friction stir welding was carried out as follow: In the first step, the stationary shoe was heated up to the specified temperature and then the FSW tool was gradually plunged toward the clamped sheets until the tool shoulder contacts with the hot shoe. This gradual movement of the tool generates sufficient heat, which plasticizes the weld zone. Then, the traversing of the tool along the joint line was initiated and continued to the end of the weld seam. After a large trial and error experiments, the acceptable ranges of rotational speed, shoe temperature and traverse speed were determined using visual inspection of the generated weld joint. The high transparency of PMMA allows an initial non-destructive testing of the weld. In the acceptable range, three levels of rotational speed (900, 1250, 1600 rpm), three levels of traverse speed (12.5, 16, 20 mm/min) and three levels of shoe temperature (40, 70, 110 $^0$C) were considered for further studies. A full factorial experiment was conducted in the following.

## 3. Results and Discussions

In order to evaluate the prepared joint mechanical properties, tensile test and hardness measurement were conducted for all samples. Tensile tests of the samples were performed according to ASTM D 638 using a Santam universal apparatus STM250 at a crosshead speed of 20 mm/min. Standard tensile specimens were extracted from the welded samples using water jet cutting. The geometrical dimensions of the tensile test specimens are shown in Figure 3.

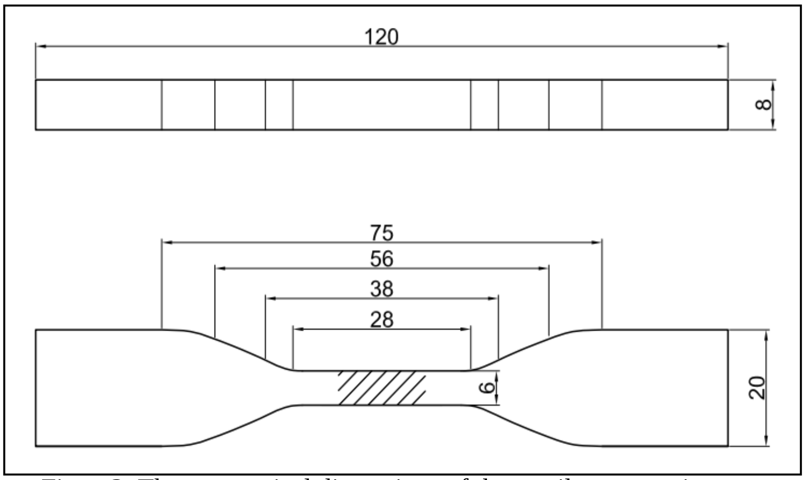

Figure3. The geometrical dimensions of the tensile test specimens

In the following, variations of joint strength of 27 welded samples at different rotational speed, shoe temperature and traverse speeds have been studied and discussed. In order to evaluate the prepared joint mechanical properties, tensile test and hardness measurement were conducted for all the prepared samples. The obtained results are listed in Table 2.

In Figure 4, the variation of joint strength/PMMA tensile strength is presented for different tool rotational and traverse speeds and shoe temperature.

Table2. Results of the tension and hardness tests

| RS [rpm] | TS [mm/min] | Heating Temperature [°C] | UTS [MPa] | $UTS/UTS_{PMMA}$ [%] | e [%] | $e/e_{PMMA}$ [%] | H [ShoreD] | $H/H_{PMMA}$ [%] |
|---|---|---|---|---|---|---|---|---|
| 900 | 12.5 | 40 | 63.7 | 79.6 | 2.6 | 130 | 61.2 | 85 |
| 900 | 12.5 | 70 | 66.9 | 83.6 | 2.8 | 140 | 62.4 | 86.6 |
| 900 | 12.5 | 110 | 72.6 | 90.7 | 3.2 | 160 | 64.3 | 89.3 |
| 900 | 16 | 40 | 62.6 | 78.2 | 2.4 | 120 | 60.3 | 83.7 |
| 900 | 16 | 70 | 64.7 | 80.8 | 2.6 | 130 | 61.4 | 85.2 |
| 900 | 16 | 110 | 65.8 | 82.2 | 3 | 150 | 62.3 | 86.5 |
| 900 | 20 | 40 | 61.4 | 76.7 | 2.2 | 110 | 59.6 | 82.7 |
| 900 | 20 | 70 | 61.9 | 77.3 | 2.4 | 120 | 60.4 | 83.8 |
| 900 | 20 | 110 | 62.3 | 77.8 | 2.8 | 114 | 61.3 | 85.1 |
| 1250 | 12.5 | 40 | 69.2 | 86.5 | 3.1 | 155 | 63.3 | 87.9 |
| 1250 | 12.5 | 70 | 72.7 | 90.8 | 3.4 | 170 | 64.4 | 89.4 |
| 1250 | 12.5 | 110 | 76.4 | 95.5 | 3.8 | 190 | 65.6 | 91.1 |
| 1250 | 16 | 40 | 63.1 | 78.8 | 2.4 | 120 | 62.1 | 86.2 |
| 1250 | 16 | 70 | 64.2 | 80.2 | 2.6 | 130 | 63.4 | 88 |
| 1250 | 16 | 110 | 68.6 | 85.7 | 3.2 | 160 | 64.2 | 89.1 |
| 1250 | 20 | 40 | 62.6 | 78.2 | 2.2 | 110 | 61.5 | 85.4 |
| 1250 | 20 | 70 | 63.7 | 79.6 | 2.4 | 120 | 62.1 | 86.2 |
| 1250 | 20 | 110 | 64.5 | 80.6 | 2.8 | 140 | 63.6 | 88.3 |
| 1600 | 12.5 | 40 | 70.6 | 88.2 | 3.6 | 180 | 67.6 | 93.8 |
| 1600 | 12.5 | 70 | 73.4 | 91.7 | 4.2 | 210 | 69.4 | 96.3 |
| 1600 | 12.5 | 110 | 80.6 | 100.7 | 5.3 | 265 | 73.7 | 102.3 |
| 1600 | 16 | 40 | 69.5 | 86.8 | 3.1 | 155 | 66.4 | 92.2 |
| 1600 | 16 | 70 | 72.1 | 90.1 | 3.4 | 170 | 67.8 | 94.1 |
| 1600 | 16 | 110 | 76.1 | 95.1 | 3.8 | 190 | 68.2 | 94.7 |
| 1600 | 20 | 40 | 68.3 | 85.3 | 2.6 | 130 | 65.3 | 90.6 |
| 1600 | 20 | 70 | 71.4 | 89.2 | 3.2 | 160 | 66.4 | 92.2 |
| 1600 | 20 | 110 | 73.7 | 92.1 | 3.5 | 175 | 67.2 | 93.3 |

TS: Traverse speed, RS: Rotation speed, UTS: Ultimate Tensile Strength, e: Elongation, H: Hardness.

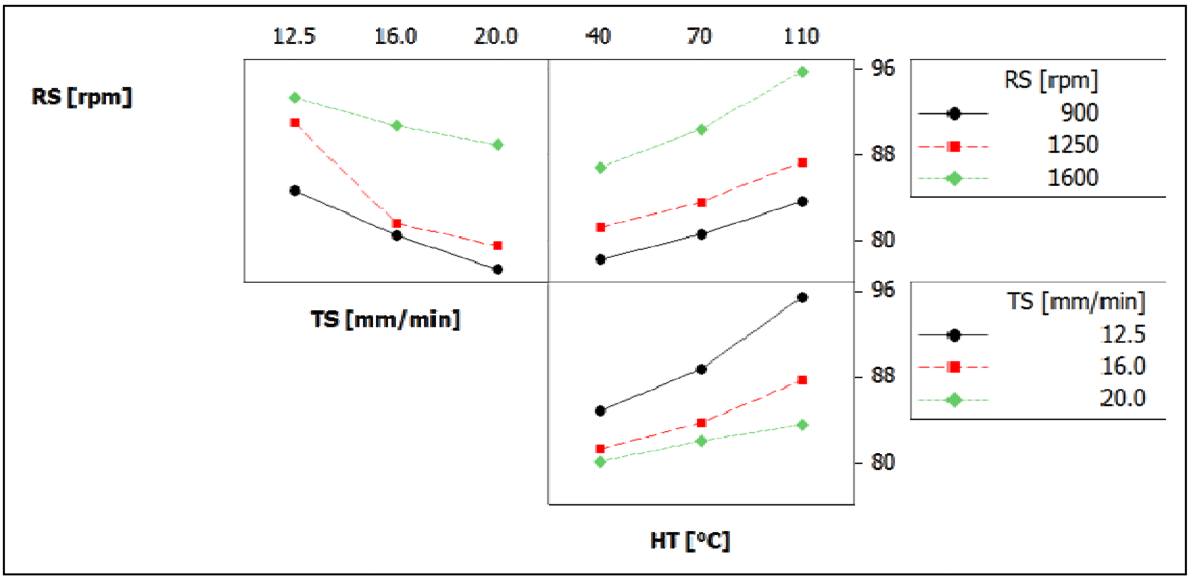


Figure4. The variation of (weld strength / PMMA strength) % versus the tool rotational speeds, traverse speeds and heating temperature

As can be seen, increasing the tool rotational speed increases the joint strength. Low spindle rotational speed leads to insufficient flow of the material in the weld zone and lack of fusion between the weld and the base material [16]. The frictional heat and the stirring of the pin increase with higher tool rotational speed [17]. Increasing the tool rotation speed from 900 rpm to 1600 rpm generates sufficient heat for better softening and plasticizing of the material around the rotating tool. Although high rotational speeds lead to better mixing of welding material and higher tensile strength, welding in excessive rotational speeds (more than 1600 rpm) causes localized melting of PMMA which leads to porosity formation and consequent deterioration of joint mechanical properties and puts the welding procedure in an uncontrollable situation. High traverse speeds lead to poor mixing of the material and consequently decrease the joint tensile strength. By the way, it seems that higher traverse speeds prevent the hot shoe and the rotating pin to heat the weld area sufficiently. The effect of traverse speed on the weld appearance was obvious. Weld line deflection and deformation in samples are the outcomes of higher traverse speed. The maximum tensile strength was obtained from the specimens prepared at tool rotational speed of 1600 rpm, traverse speed of 12.5 mm/min and shoe temperature of 110℃ which was equal to 95% of base polymer strength. The variations of welded joints elongation are also shown in Fig. 5. As it is obvious in this figure, the variations of elongation as a function of tool rotational speed, shoe temperature and traverse speed follow the same trend as the tensile strength.

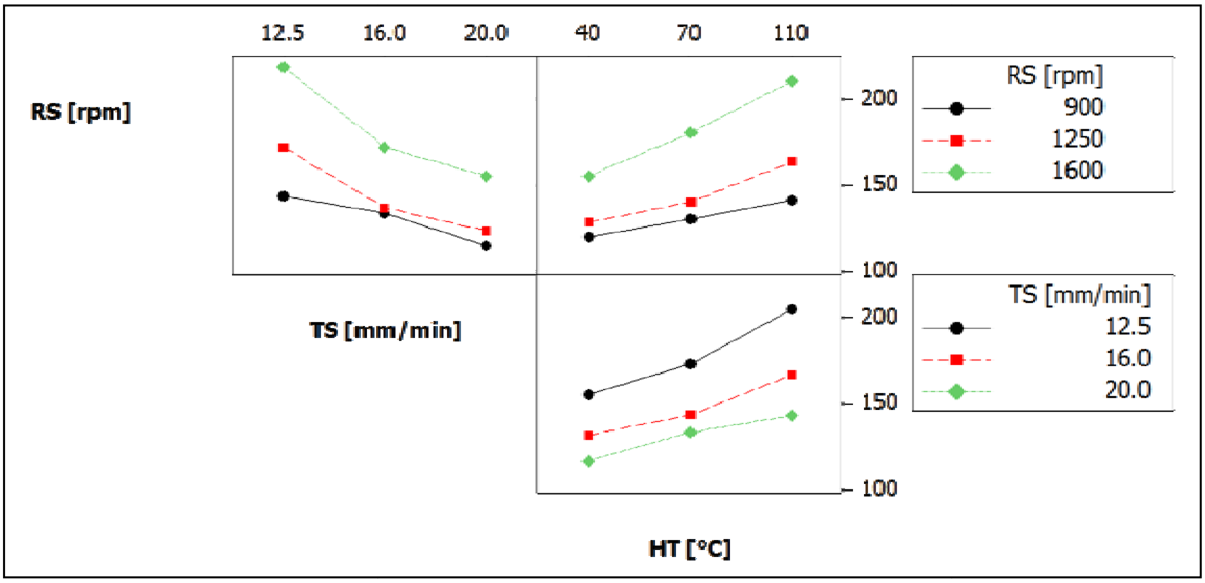


Figure5. The variation of (joint elongation / PMMA elongation) % versus the rotational speeds, traverse speeds and heating temperature

By increasing the tool rotational speed to 1600 rpm, increasing the shoe temperature and decreasing the traverse speed, elongation of the specimens was increased. Similarly, a maximum elongation of 2.65 times of PMMA elongation was obtained at tool rotational speed of 1600 rpm, traverse speed of 12.5 mm/min and shoe temperature of 110℃. Hardness is a criterion to estimate the material behavior against plastic deformation. Hardness value can also be utilized for indirect evaluation of mechanical properties. In the current paper, hardness measurement was carried out using shore D hardness scale. Shore hardness is the recommended method for measuring the hardness of rubbers and elastomers [18]. Fig. 6 illustrates the effect of the process parameters on the hardness of the welded samples. Again, the increase in the rotational speed from 900 rpm to 1600 rpm improves the hardness of the sample due to sufficient heat generation which allows proper material flow and better combination of pasty materials. Our primary studies at rotational speed higher than 1600 rpm showed that the extra heat generation melts the PMMA plates which are accompanied by more weld defects at the interface and consequently decreases the joint mechanical properties.

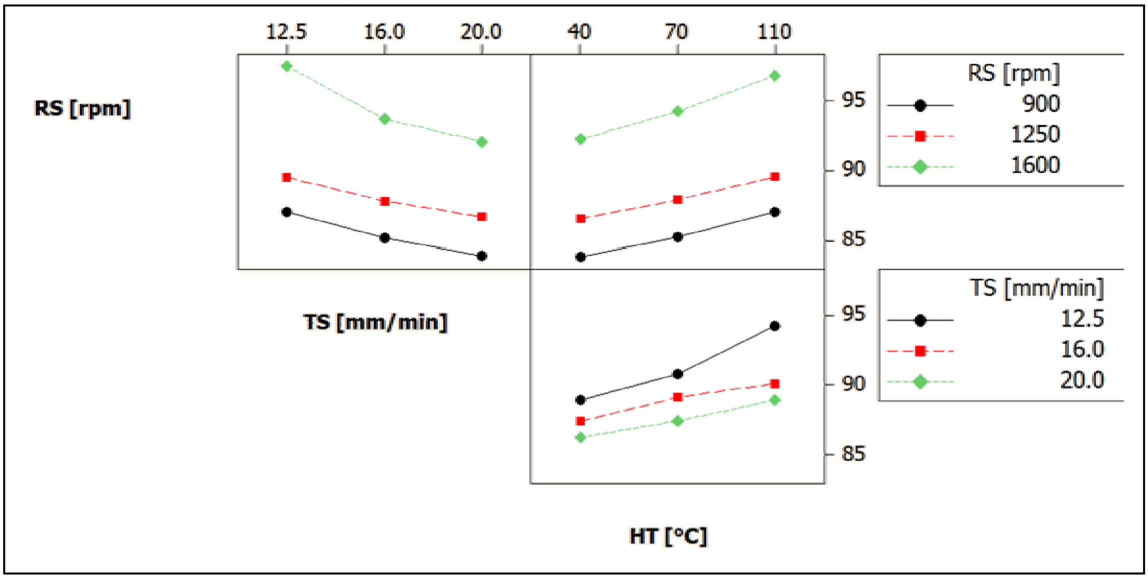


Figure6. The variation of (weld hardness / PMMA hardness) % versus the rotational speeds, traverse speeds and heating temperature

Figure 6 depicts that applying the highest applicable rotational speed of 1600 rpm, lowest traverse speed of 12.5 mm/min and shoe temperature of 110$^0$C leads to the highest weld hardness value 80.7 D which is slightly higher than the PMMA hardness.

## 4. Conclusion

In this paper, the hybrid thermal assisted friction stir welding of thermoplastic polymer sheets of PMMA was carried out successfully. As the mechanical property, tensile strength, elongation and hardness of the friction stir welded PMMA sheets were studied. The following conclusions could be drawn from the experimental results:

- A hybrid thermal assisted friction stir welding approach was developed.
- At optimum condition, the joint strength equal to 95% of PMMA strength was obtained.
- Enhancement up to 265% in joint elongation in comparison to PMMA sheet was achieved.
- Maximum weld strength was obtained by highest applicable rotation speed and shoe temperature.
- Weld elongation and hardness versus process parameters follow the same trend as weld strength.

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