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Friction Stir Welding of Dissimilar Poly Methyl Methacrylate and Polycarbonate 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.The aim of this study is to investigate the weldability of dissimilarpoly methyl methacrylate and polycarbonatesheets via friction stir welding approach.The effects of process parameters such as rotational and traverse speeds and the heater temperature on the mechanical properties of the joints were studied comprehensively. Rotational and traverse speeds and heater temperature of 2100 rpm, 8 mm/min and 120 °C, offered the optimized mechanical properties of the joint. In the optimum joining condition, welded joint with strength equal to 98% of polycarbonate and with higher hardness than the polycarbonate was obtained.

Keywords

Thermoplastic Polymer, Poly Methyl Methacrylate, Polycarbonate, Heat Assisted Friction Stir Welding

1. Introduction

Modern thermoplastic materials are used in an expanding range of engineering applications, such as in the automotive industry, due to their enhanced stress-to-weight ratios and toughness. Even though plastics offer a high degree of design freedom and processing ability, the fabrication of larger and complex parts usually requires joining technologies [1], such as laser welding [2], vibration welding [3], friction stir spot welding [4] and friction stir welding [5] which are considered to be effective in different areas of industry. As a relatively new method, friction stir welding (FSW) invented in 1991 at the welding institute (TWI) has turned out to be a promising way of solid-state joining of difficult-to-join materials along with great mechanical properties [6]. The method can guarantee high quality, efficiency, energy saving, and environmental protection [7]. Heat is generated by friction between the rotating tool and the base material, which softened the region near the FSW tool. The traverse movement of tool along the joint line intermixes the workpieces mechanically and forges the softened material by the mechanical pressure [8]. The FSW process was first utilized for Aluminum alloys [9], but as the time went on, FSW showed large potential for joining magnesium alloys [10], steel alloys [11], titanium alloys [12], copper alloys

[13], metal matrix composites [14] and dissimilar materials [5]. A simple schematic of FSW process is shown in Figure 1 [15].

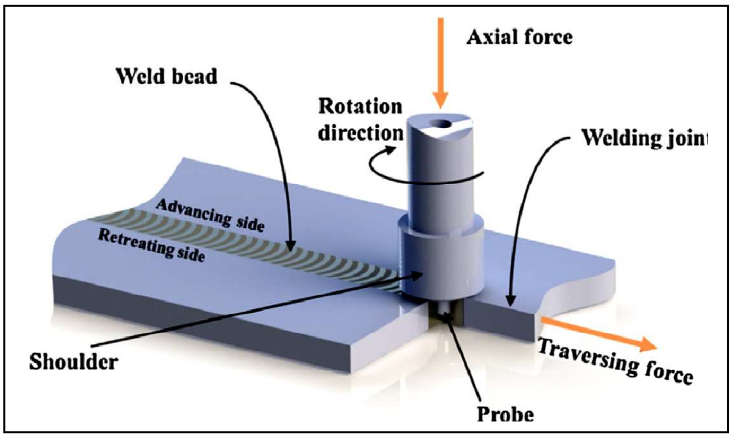

Figure1. Schematic view of the FSW process [15]

2. Background

Recently, some researchers have studied the application of FSW on the thermoplastics polymers. Arici and Sinmaz [16] studied the effect of double passes of the tool on FSW of polyethylene. Double passes allowed them to increase the joint mechanical properties. Saeidi et al. [17] studied the properties of plastic sheets joined by conventional FSW tool, presented low tensile strength (25% of base polypropylene (PP) composite strength). Strand et al. [18] studied the mechanical and microstructure properties of polypropylene (PP) friction stir welded sheets using hot shoe method. They finally came to the conclusion that to achieve the minimal disruption of polymer microstructure, welds should be made at low feed rate, high shoe temperature, long pressure time and large pin diameter. Erica Anna Squeo et al. [19] studied friction stir welding of polyethylene (PE) sheets. They declared that even if the friction stir welding process in polymeric materials seems a promising technique because of some advantages over other joining technologies, as the low cost of machine and tooling cost, it is not a ripe technology yet. They found that in order to make the process more robust, gain higher strengths and obtain more process repeatability, heating the plastic material is a good way using a hot tool process. Mustafa Aydin [20] studied the effect of preheating on the FSW of Ultra high molecular weight polyethylene (UHMWPE). The preheating enabled the plastic material to be easily stirred. It was concluded that the achieved weld efficiency is 89% of base material. Sadeghian and Besharati [21] studied the mechanical properties of friction stir welding of thermoplastic acrylonitrile butadiene styrene (ABS). Statistical optimization, using response surface method, was used to investigate the mechanical strength of the welded samples. Hosein et al. [22] 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 resistances of the welded samples reach to the base material resistance. The stress-strain behavior of the welded joint was also modeled using mathematical methods. Kiss and Czigány [23] employed conventional friction stir welding process for joining of polypropylene sheets. They examined the effects of process parameters on the joint strength. The maximum joint strength equal to 50% of base material was achieved. Joining the dissimilar polymethyl methacrylate (PMMA) and acrylonitrile butadiene styrene (ABS) sheets were conducted using friction stir spot welding by Dashatan et al. They found that this method was a feasible way to weld dissimilar polymers. They also demonstrated that the process parameters have a significant impact on the weld strength [4]. Rezaee et al. [24] 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. In the present study, the influences of rotational and traverse speeds and heater temperature on the mechanical properties of dissimilar PC and PMMA joints are studied. For evaluating the mechanical properties of the welded joints, tensile and hardness tests were conducted for all welded samples.

2. Materials and Methods

2.1 Materials

In this paper, the Polycarbonate (PC) and Poly methyl methacrylate (PMMA) sheets were used as the base material. Polycarbonates (PC) are a group of thermoplastic polymers containing carbonate groups in their chemical structures. Polycarbonates used in engineering are strong, tough materials, and some grades are optically transparent. They are easily worked, molded, and thermoformed. Because of these properties, polycarbonates find many applications. On the other hand, Poly methyl methacrylate (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 [25]. The summary of the physical properties of PC and PMMA is presented in Table1.

Table1. The physical properties of Polycarbonate and Poly methyl methacrylate polymers

Material	Tensile Strength [MPa]	Durometer Hardness [ShoreD]	Melting point Temperature [^{0}C]	Density [g/cm^3]
Polycarbonate (PC)	76	70	150	1.20
Poly methyl methacrylate (PMMA)	80	79	160	1.18

2.2 Tool Design

The designed tool in the present work was consisting of three main parts: a cylindrical rotating pin, a stationary shoulder or shoe,and heating system. The photograph of FSW tool is shown in Figure 2. As it can be seen in this figure, the tool pin is inserted into the shoeshaped shoulder and a heater, which is equipped with a close-loopthermo controller, is located inside the shoe. Through an indicator,this device shows the approximate temperature of the melting areaand with a thermal potentiometer, the heat output of the electricheater could be adjusted. Furthermore, a thrust bearing separatedthe shoe from the pin and its main purpose was to hold the shoulder stationary relative to pin during FSW. The tool pin was made ofH13 hot-working steel and shoulder’s material was 7075 aluminumowing to its high thermal conductivity and mechanical strength.The shoulder's surface was coated with PTFE (Teflon) in order toprevent the stick phenomenon that may occur between hot aluminum and polymeric surface.

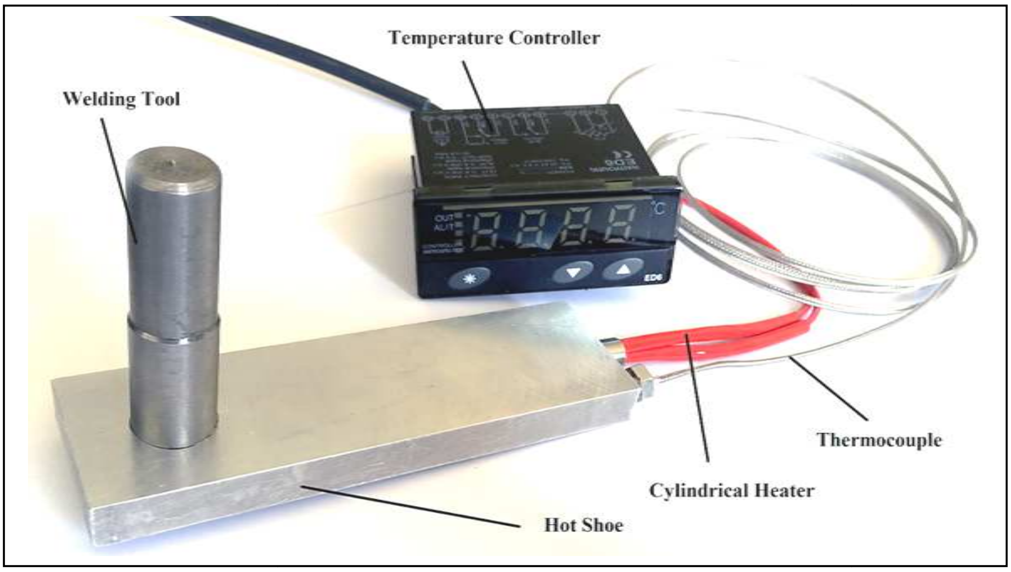

Figure2. Photograph of the designed friction stir welding tool

The tool and shoulder dimensions are illustrated in Figure 3.

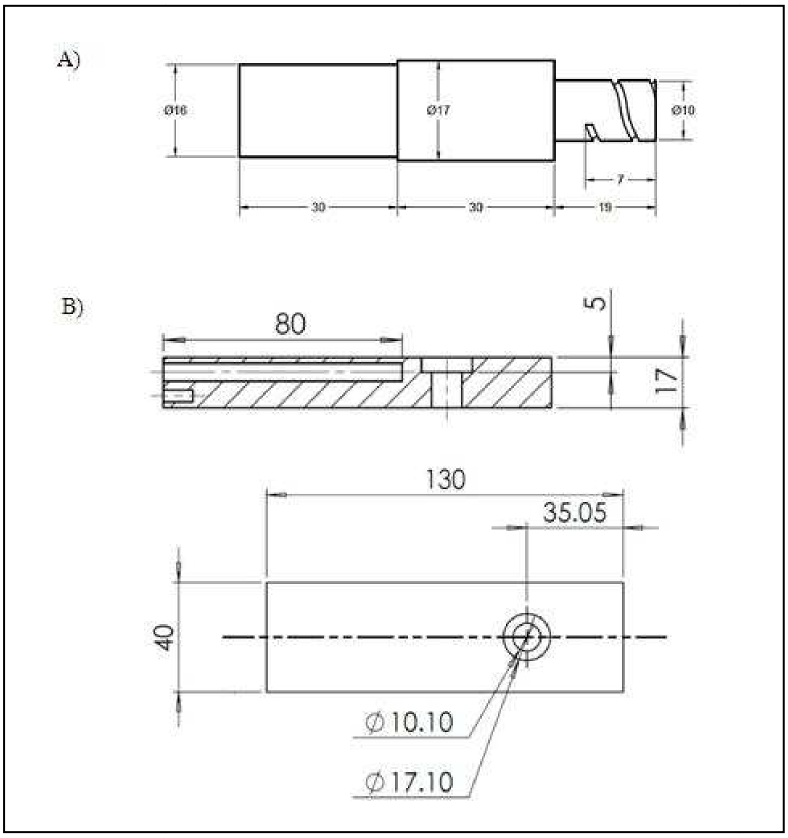

Figure3. Drawings of the designed FSW tool: (a) pin and (b) shoulder (shoe)

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. In the acceptable range, three levels for rotational speed (750, 1540, 2100 rpm), three levels for traverse speed (8, 12, 20 mm/min) and three levels for shoe temperature (30, 70, 120℃) were considered for further studies. A full factorial experiment was conducted in the following.

3. Results and Discussions

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.

3.1 Strength of the Welded Joints

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 4.

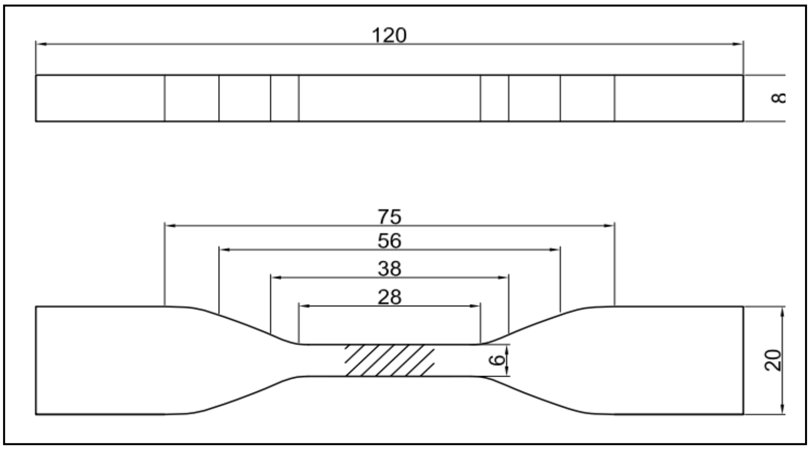

Figure4.The geometrical dimensions of the tensile test specimens

Table2. Results of the tension and hardness tests

RS [rpm]	TS [mm/mm]	HT [°C]	UTS [MPa]	UTS/UTS_{PC} [%]	H [shore D]	H / H_{PC} [%]
750	8	30	62.1	81.7	52.2	74.5
750	8	70	64.6	85	54.5	77.8
750	8	120	66.3	87.2	56.7	81
750	12	30	61.4	80.7	51.3	73.2
750	12	70	62.7	82.5	52.9	75.5
750	12	120	64.3	84.6	54.8	78.2
750	20	30	59.3	78	48.4	69.1
750	20	70	60.2	79.2	50.5	72.1
750	20	120	62.6	82.3	52.7	75.2
1540	8	30	65.1	85.6	58.7	83.8
1540	8	70	68.6	90.2	55.4	79.1
1540	8	120	70.2	92.3	58.6	83.7
1540	12	30	64.4	84.7	54.1	77.2
1540	12	70	67.3	88.5	57.6	82.2
1540	12	120	68.4	90	53.4	76.2
1540	20	30	63.3	83.2	55.2	78.8
1540	20	70	65.1	85.6	57.5	82.1
1540	20	120	67.2	88.4	60.3	86.1
2100	8	30	70.4	92.6	60.2	86
2100	8	70	72.5	95.3	62.6	89.4
2100	8	120	74.6	98.1	64.7	92.4
2100	12	30	68.6	90.2	58.1	83
2100	12	70	71.3	93.8	61.7	88.1
2100	12	120	73.2	96.3	63.9	91.2
2100	20	30	67.3	88.5	57.5	82.1
2100	20	70	70.1	92.2	60.7	86.7
2100	20	120	71.4	93.9	61.3	87.1

RS: Rotation speed, TS: Traverse speed, HT: Heating Temperature, UTS: Ultimate Tensile Strength, H: Hardness

In Figure 5, the variation of joint strength/PC- PMMA tensile strength is presented for different toolrotational and traverse speeds and shoe 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 [26]. The frictional heat and the stirring of the pin increase with higher tool rotational speed [27]. Increasing the tool rotation speed from 750 rpm to 2100 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 2100 rpm) causes localized melting of PC-PMMA which leads to porosity formation and consequent deterioration of joint mechanical properties and puts the welding procedure in an uncontrollable situation.

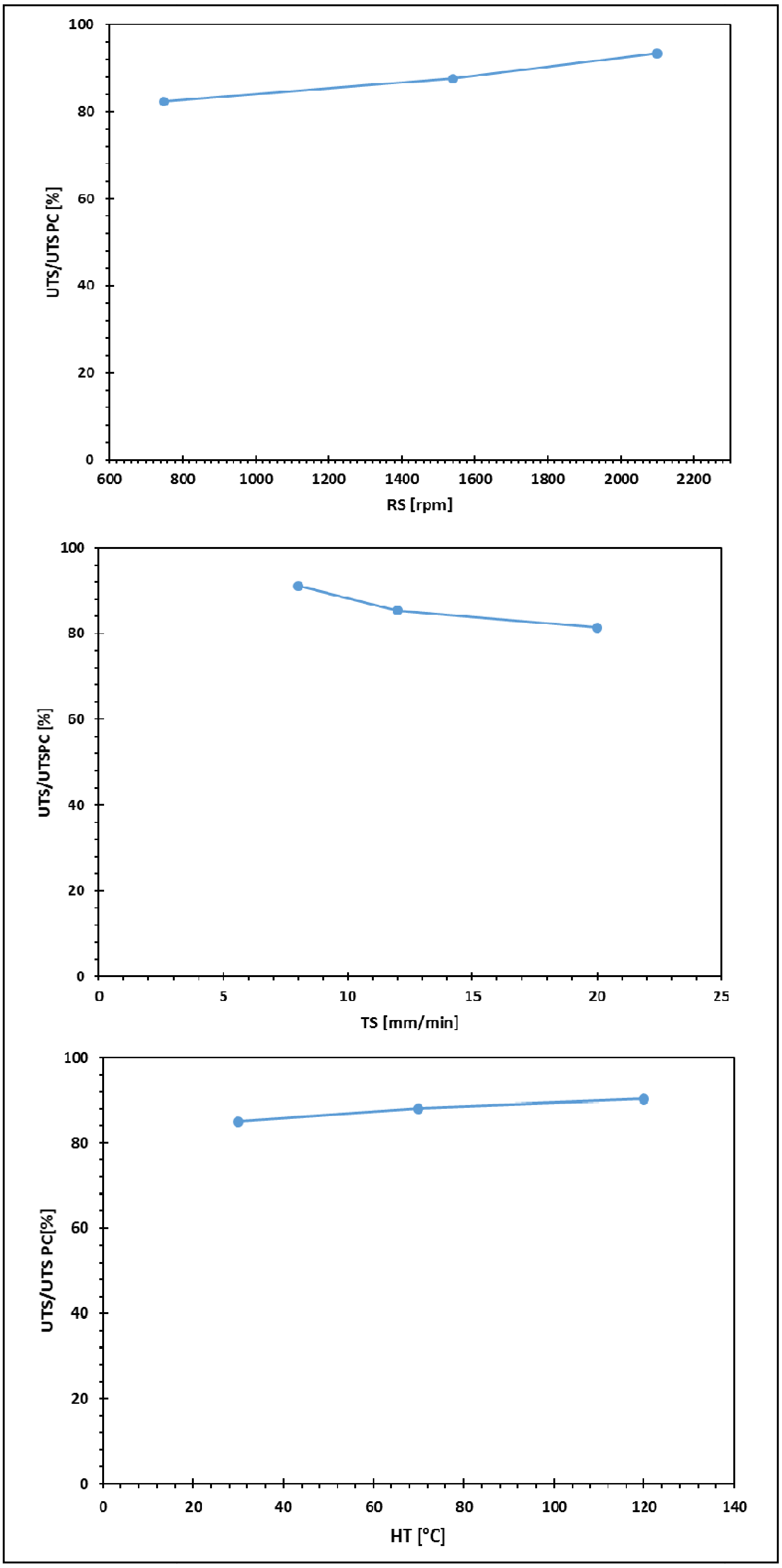

Figure5**.** Interaction plot for joint ultimate tensile strength PC-PMMA ultimate tensile strength

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 2100 rpm, traverse speed of 8 mm/min and shoe temperature of 120℃ which was equal to 98% of base polymer strength.

3.2. Hardness of the Welded Joints

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 [28]. Figure 6 illustrates the effect of the process parameters on the hardness of the welded samples. Again, the increase in the rotational speed from 750 rpm to 2100 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 2100 rpm showed that the extra heat generation melts the PC-PMMA plates which are accompanied by more weld defects at the interface and consequently decreases the joint mechanical properties.

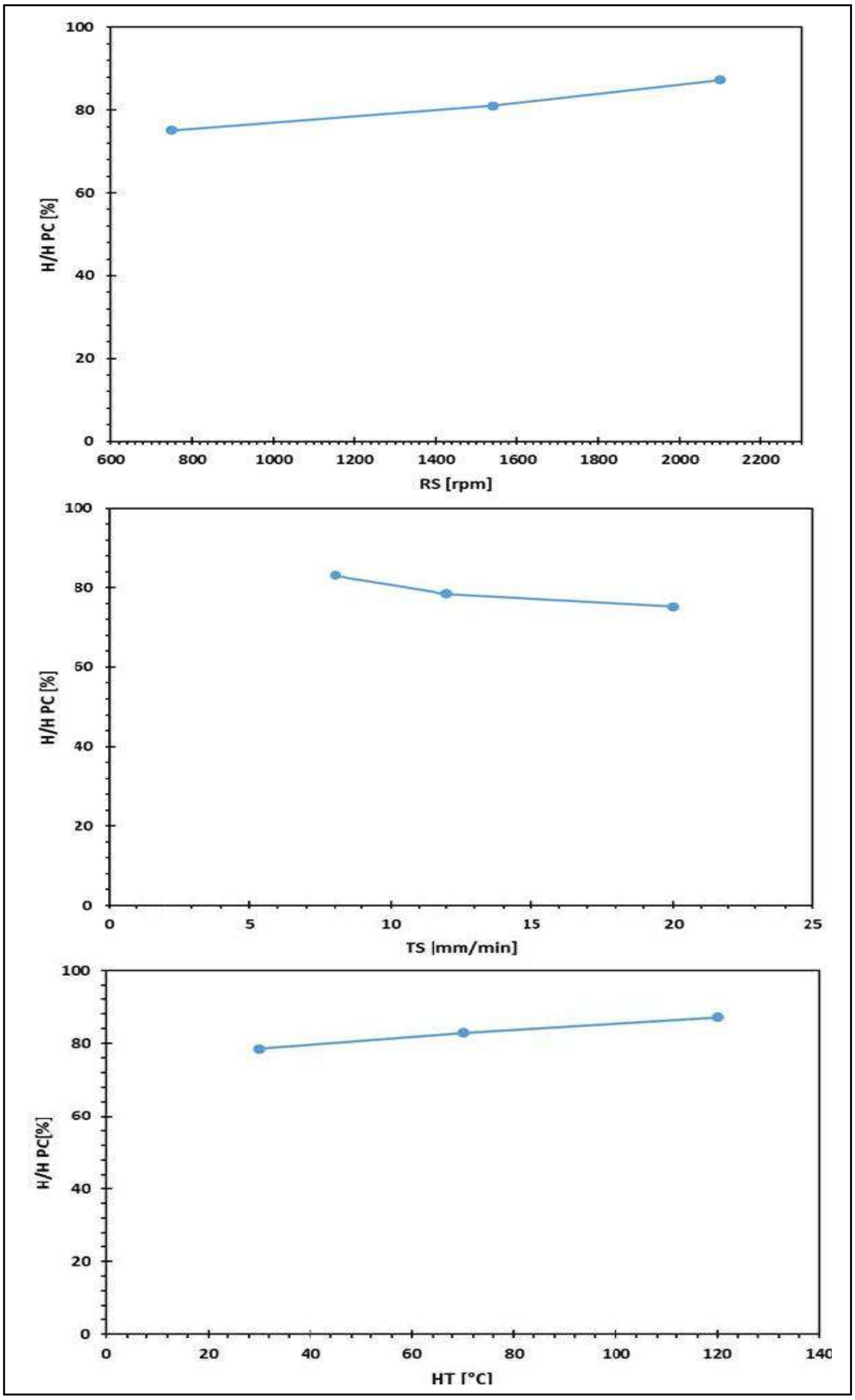

Figure6. Interaction plot for joint hardness PC-PMMA hardness

4. Conclusion

Dissimilar joining of PC and PMMA polymers was successfully carried out in this study using hybrid thermal assisted friction stir welding approach. In optimum condition, welded joint with defect-free with strength equal to 98% of polycarbonate and with higher hardness than the polycarbonate was obtained. Based on the experimental studies, the following important results have been drawn:

- A hybrid thermal assisted friction stir welding approach was developed.
- At optimum condition, the joint strength equal to 98% of PC and PMMA strength was obtained.
- Maximum weld strength was obtained by highest applicable rotation speed and shoe temperature.
- Weld hardness versus process parameters follows the same trend as weld strength.

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