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Research Article

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Influence of Tool Pin Geometry in Friction Stir Spot Welded Polymer Sheets

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Abstract The effect of important welding parameters and tool properties that are effective on static strength in friction stir spot welds of polymer sheets were studied. Different tool pin profiles with different pin length and pin angle were used to fabricate the joints. The tool rotational speed, tool plunge depth and dwell time were determined welding parameters. All the welding operations were done at the room temperature. Lap-shear tests were carried out to find the weld static strength. Weld cross section appearance observations were also done. From the experiments, the effect of pin profile, pin length, pin angle and tool rotational speed on friction stir spot welding formation and weld strength was determined.

Keywords polymers (thermoplastics), friction-stir spot welding, polymer welding, welding parameters

Introduction

In 2001, friction stir spot welding (FSSW) was developed in the automotive industry to replace resistance spot welding for aluminum sheets [1]. FSSW of metals is a solid-state welding process. The friction stir spot welding (FSSW) process has been successfully applied to thermoplastic sheets since 2003 [2]. The FSSW process of thermoplastics consists of four phases; plunging, stirring, solidifying and retracting as shown in Figure 1 [3]. The rotating tool is plunged into the attached work pieces with force to a certain depth. In the stirring phase the tool doesn't plunge. Frictional heat is generated in the plunging and the stirring phase and thus, the material adjacent to the tool is heated and melted [3]. The melted upper and lower work piece materials mix together in the stirring phase. When a predetermined amount of melt is obtained, the tool rotation stops. The tool is held for a while in the work pieces to solidify the liquid material under tool pressure and to form the nugget which joins the work pieces. The holding time of the tool was named as the dwell time. Then the tool is retracted. FSSW of polymers is not a solid-state welding process, it is a fusion welding method.

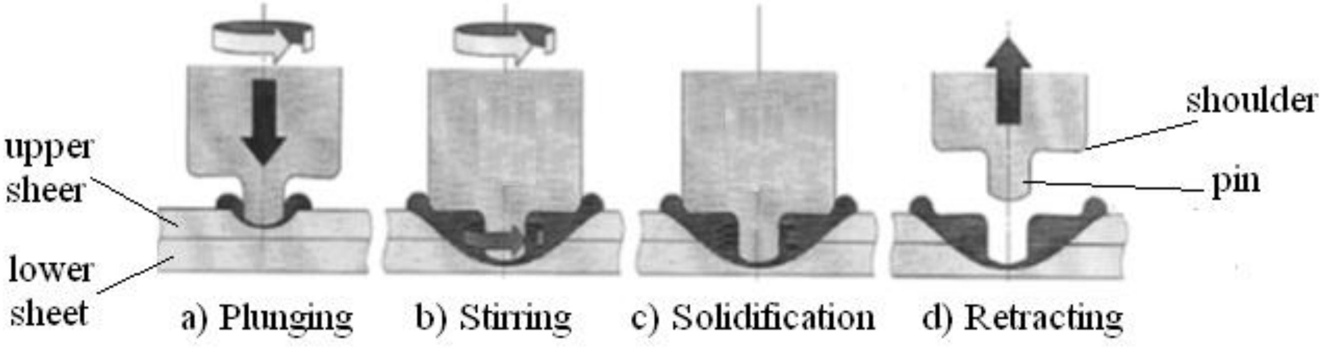

Figure 1: Four phases of friction stir spot welding process: (a) plunging, (b) stirring, (c) solidifying and (d) retracting [3].

During FSSW the heat is generated at the interface of rotating tool and the work piece due to friction. The tool geometry and welding parameterseffect heat generation, joint formation and strength of welds in FSSW [4]. The tool consists of two parts [5]: the shoulder and the pin.The pin generates friction heat, deforms the material around it and stirs the heated material [6]. The size of the pin [7], the pin angle [8], pin thread orientation [9], pin length [10] and pin profile [11] were found important in nugget formation. The shoulder of the tool generates heat during the welding process, forges the heated material, prevents material expulsion and assists material movement around the tool [12]. The size of the shoulder and its concavity are also important in friction stir spot welding [13].

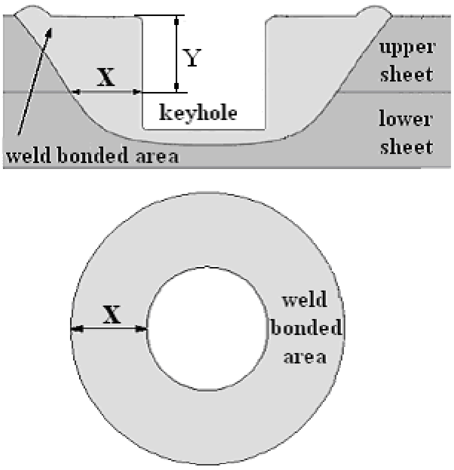

Figure 2: (a) Schematic illustration of the cross section of a friction stir spot weld, (b) Geometry of the weld bond area[4]: X, nugget thickness; Y, the thickness of the upper sheet[14].

The weld zone of a FSSW joint is schematically shown in Figure 2a [4]. The resulting weld has a characteristic keyhole in the middle of the joint as shown in Figure 2a. From the appearance of the weld cross section, two particular points can be identified: (1) The thickness of the weld nugget (X) and (2) The thickness of the upper sheet under the shoulder indentation (Y). The thickness of the weld nugget is an indicator of the weld bond area (Figure 2b). The weld bond area increases with the nugget thickness. The size of the thickness of the weld nugget and the weld bond area determine the strength of a FSSW joint [3]. The size of the upper sheet thickness under the shoulder indentation also determines the strength of a FSSW joint [14].

In this study we intended to investigate the effects of tool pin geometry on weld properties of high density polyethylene (HDPE) and polypropylene (PP) FSSW joints. In this paper, we focused on the effects of the pin profile, size of the pin, the pin angle and pin lengthon weld nugget formation and the weld strength.

Materials and Methods

In this investigation, 4 mm thick HDPE and PP sheets were used. The specimens were welded in a milling machine. A spot weld joint was obtained in the middle of the specimen. Figure 3 illustrates a magnified cross sectional view of the SAE 1050 steel tool used in the welding. The tool dimensions are shown in Figure 3. In all tools the shoulder diameter was 30 mm and concavity angle was 6 degrees. Three different tool pin profiles (straight cylindrical, tapered cylindrical and threaded cylindrical) were used to fabricate the joints (Figure 4). In straight cylindrical, tapered cylindrical and threaded cylindrical pins, the pin diameter wasdetermined by measuring the bottom diameter of the pin. The threaded cylindrical pin was produced bya standard M8 thread cylindrical pin was formed and then, the pin of the tool was milled to a 7.5 mm diameter. The tool dimensions and their ranges employed in this study are given in Table 1. In every welding the rotating tool plunged into the workpieces with a 3.3 mm/s constant plunge rate down to the 0.2 mm depth at an accuracy of ±0.02 mm.The welding parameters and the shoulder geometry was chosen according to the published FSSW results of HDPE and PP sheets[3,4,15-21].All the welding operations were done at the room temperature. At each welding condition 6 lapshear test specimens were produced. Five of them were mechanically tested and the sixth one was metallographically examined.

Welded lap-shear specimens were tested on an Instron machine at a constant crosshead speed of 5 mm/s. The load and displacement were simultaneously recorded during the test. The lap-shear strength was obtained by averaging the strengths of five individual specimens, which were welded with identical welding parameters. Weld cross section appearance observations of the joints were done with a video spectral comparator at 12.88magnification. For macro structure studies, thin slices (30 m) were cut from the welded specimens using a Leica R6125 model rotary type microtome. These thin slices were investigated using VSC-5000 model video spectral comparator. The photographs of the cross sections were obtained.

Table 1: Welding parameters and their ranges.

Parameters	Units	Ranges
Tool geometry	3 types	5-11.25
Pin diameter millimeter	(mm)	7.5
Pin angle	degrees	0-25
Pin length	millimeter (mm)	4-7

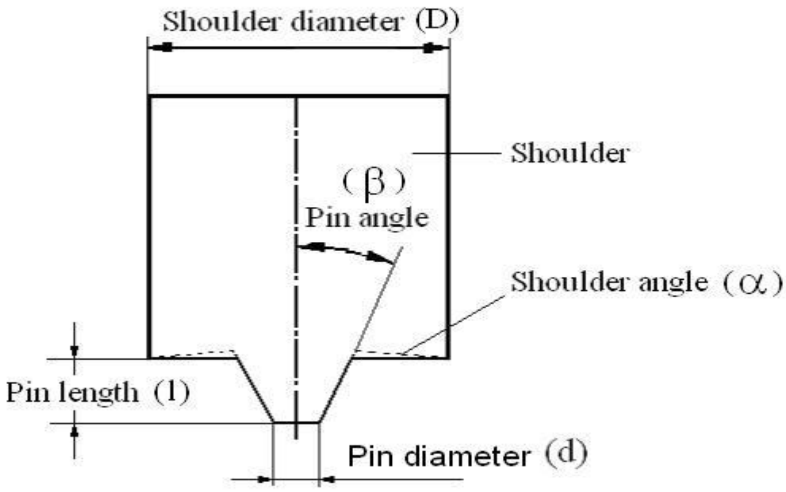

Figure 3: Friction stir spot welding tool design showing geometric parameters.

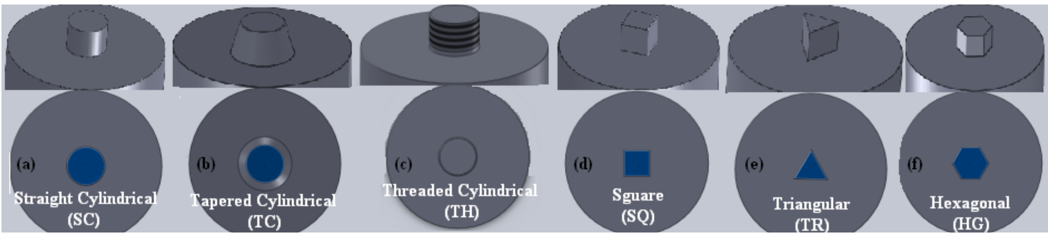

Figure 4: FSSW tool profile and pin size (a) straight cylindrical, (b) tapered cylindrical and (c) threaded cylindrical.

Conclusion

The effect of the tool pin profile on weld strength of HDPE welds was shown in Figure 5. The tapered pin gave the best strength. This joint was broken with an average force of 3580 N. The straight cylindrical pin profile gave the poorest strength. The importance of the tool pin profile in PP welds was shown in Figure 6. In these tests, each pin had a 7.5 mm pin diameter. The tapered cylindrical pin had a 15° pin angle. The maximum fracture load was obtained with the tapered cylindrical pin (4032 N). The straight cylindrical pin profile gave the lowest fracture load (3305 N). PP and HDPE welds gave the same result. The reason of this difference between the pins can be easily explained with the weld nugget thicknesses of HDPE welds which are shown in Figure 7.

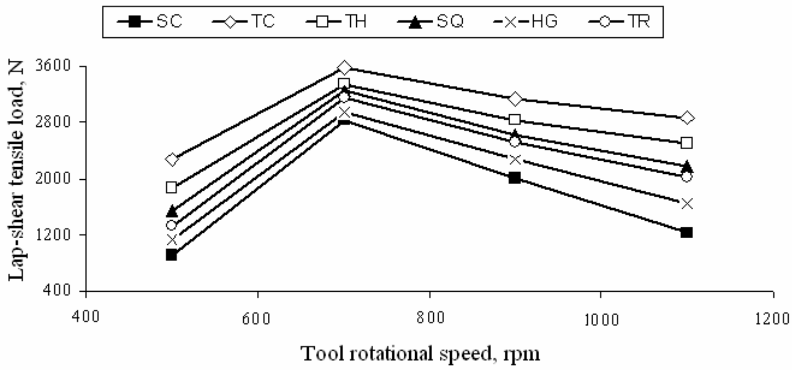

Figure 5: The effect of the tool pin profile on weld strength of HDPE welds.

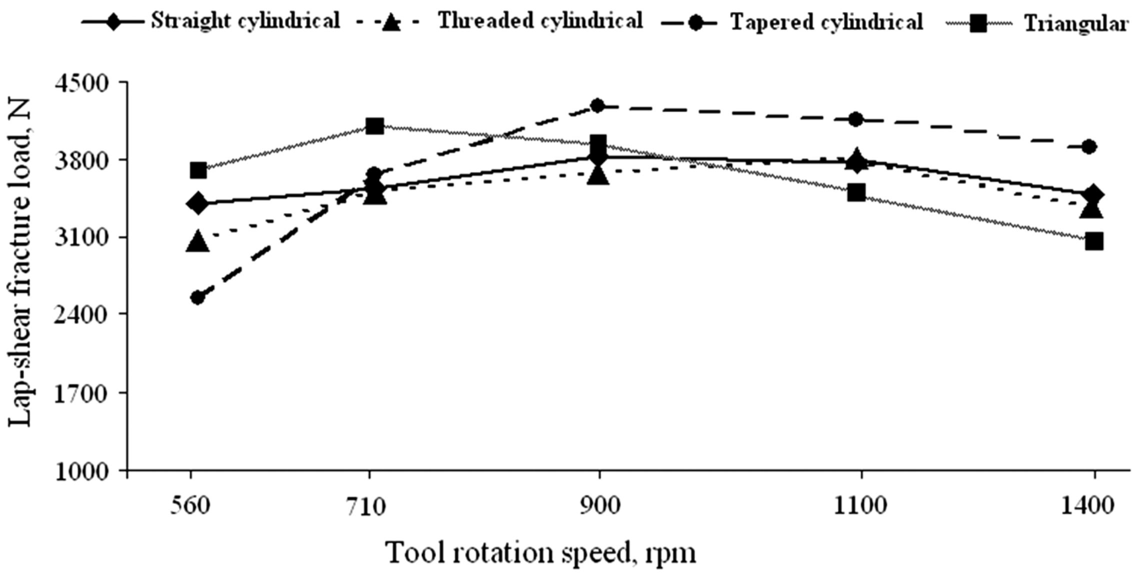

Figure 6: The effect of the tool pin profile on weld strength of PP welds.

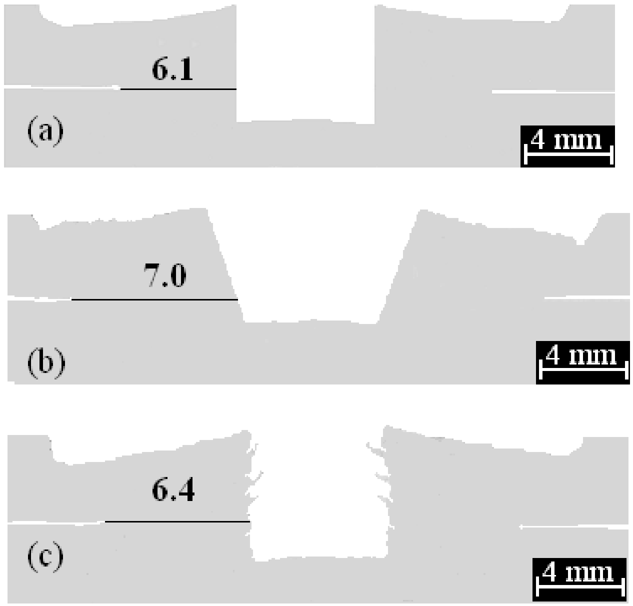

Figure 7: Effect of pin angle on weld nugget formation HDPE welds (a) straight cylindrical pin, (b)15^o pin angled tapered cylindrical pin and (c) threaded straight cylindrical pin.

The nugget thickness of the straight cylindrical is 6.1 mm, thenugget thickness of the threaded straight cylindrical pin is 6.4 mm and the nugget thickness of the 15° tapered cylindrical pin is 7.0 mm (Figure 8). These photographs show that the tapered pin produced the biggest weld bonded area and the straight cylindrical produced the smallest weld bonded area. The lap-shear fracture force of a FSSW joint is directly proportional to the nugget thickness and the weld bonded area [22]. In FSSW the generated heat in the operation determines the weld size. The more heat produced the bigger weld size is obtained. The straight cylindrical pin produced the least friction heat and the smallest, so it gave the minimum lap-shear fracture load. The threaded straight cylindrical pin mixes the heated material better than the straight cylindrical pin therefore, more friction heat was generated with this pin. A bigger weld size and a higher lap-shear fracture load was obtained with the threaded straight cylindrical pin. In FSSW of thermoplastics the welding force increases with the pin angle [4]. The tapered pin produces more friction heat and a bigger nugget thickness than the threaded straight cylindrical pinas shown in Figure 8. The heat produced in the weld area is directly proportional to the welding force [23]. A higher welding force produces more heat and a bigger weld bonded area which causes a high weld strength [14,24]. Therefore, the tapered pin produced a higher welding force than the threaded straight cylindrical pin

[13]. Therefore, the strength of the 15° tapered pin was higher than that of the threaded straight cylindrical pin (Figure 6 & 7).

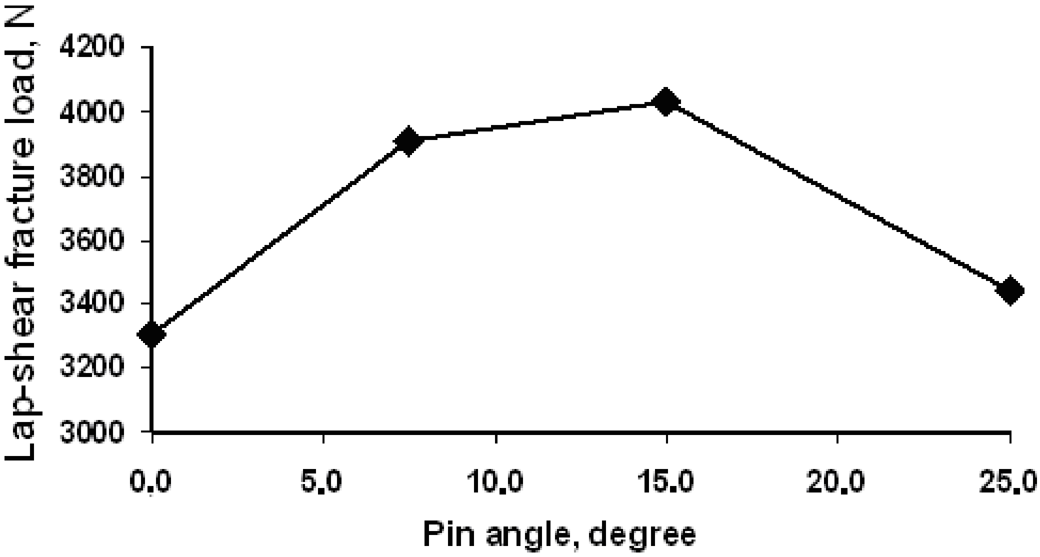

Figure 8: The effect of pin angle on the lap-shear fracture load of PP welds.

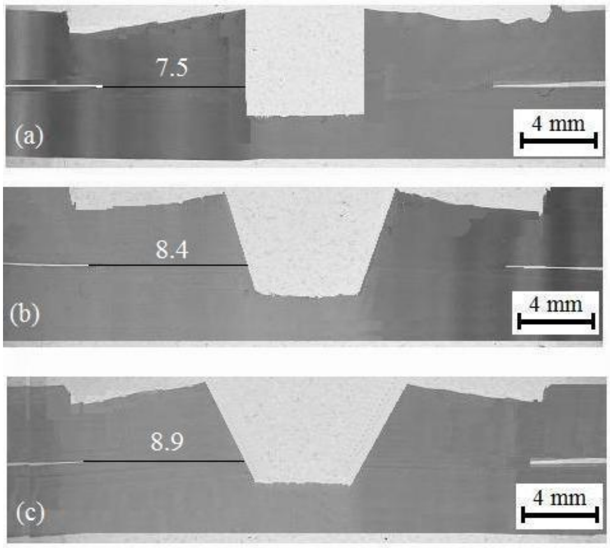

Figure 9: The effect of pin angle on weld stir zone formation of PP welds (a) threaded straight cylindrical pin, (b) 15° pin angled tapered cylindrical pin and (c) 25° pin angled tapered cylindrical pin.

The effect of the lap-shear tensile fracture load and the tool pin angle on welding zone of PP welds are shown in Figure 8 and Figure 9. Each pin had a 7.5 mm diameter at the bottom. The photographs illustrate that the size of the keyhole which formed in the welding zone was directly dependent on the pin profile. The wall slope of the keyhole changed with the pin angle of the tool. The nugget thickness is 7.5 mm for the straight cylindrical pin, 8.4 mm for the 15° pin angled tapered pin and 8.9 mm for the 25° pin angled tapered pin. The tapered pins cause an increase in welding tool force, heat generation and weld size. The effect of the tapered pin is directly proportional to the pin angle as explained in the previous paragraph. The tapered pins created thicker nuggets than the straight cylindrical pin. The straight cylindrical pin which had a 0° pin angle gave the least fracture load because of the smallest weld size. The fracture load increased with the pin angle up to 15° and then the fracture load reduced with the bigger pin angle. The nugget thickness increased with the pin angle as shown in Figure 9. Although the 25° tapered cylindrical pin had a 8.9 mm weld nugget thickness, weld strength was lower than the others. The 25° tapered cylindrical pin has produced more heat than the other pins. If a liquid thermoplastic material is heated to a high temperature and then a high pressure is applied to it, a decrease in the molecular weight of the material occurs which lowers the mechanical properties of the thermoplastic material [25]. This event that happens in thermoplastics is named as mechanical scission [26]. So, excessive pin angle caused very high-pressure and heat generation which lowered the weld strength FSSW of thermoplastics.

Figure 10 shows the effect of the pin length on the weld fracture load of PP welds. The tools used for these tests had a 15° pin angle and 7.5 mm pin diameter. The pin length was varied between 3.8–6.5 mm. The fracture load was 100 N when the weld was made with the 3.8 mm pin length tool. The pin worked as a drill. The pin did not plunge into the lower work piece. Most of the drilled material of the upper sheet was expelled out, so a very weak joint was formed with this pin. The big size nugget formation can start with the melting of the lower sheet. The lap-shear fracture load increased with the pin length from 4.5 mm up to 5.5 mm. These pins plunged into the lower work piece and melted the lower work piece. The maximum lap-shear fracture load was obtained with the tool which had a 5.5 mm pin length. The pins which were longer than 5.5 mm gave smaller fracture loads. The weld cross sections of these welds are shown in Figure 11. The nugget thickness increased with the pin length. More friction heat generated with longer pin length and bigger weld size were produced as shown in Figure 11. A long pin has a disadvantage which lowers the weld strength. The thickness of the upper sheet gets smaller with the pin length. The weld strength decreases with the decrease of the thickness of the upper sheet [3,4,13,14]. The photographs of Figure 11 and 12 reveal how the thickness of the upper sheet gets smaller with the pin length. In PP welds the nugget thickness was 8.9 mm for 6.5 mm pin length and the nugget thickness was 8.4 mm for 5.5 mm pin length. Although, a thicker nugget was produced with 6.5 mm long pin, the weld strength was lower than the weld of 5.5 mm pin length. This difference is coming from the variance of thickness of the upper sheet. Excessive pin length lowers the weld strength. The tool which had a 5.5 mm pin length was found optimum for PP and HDPE welds.

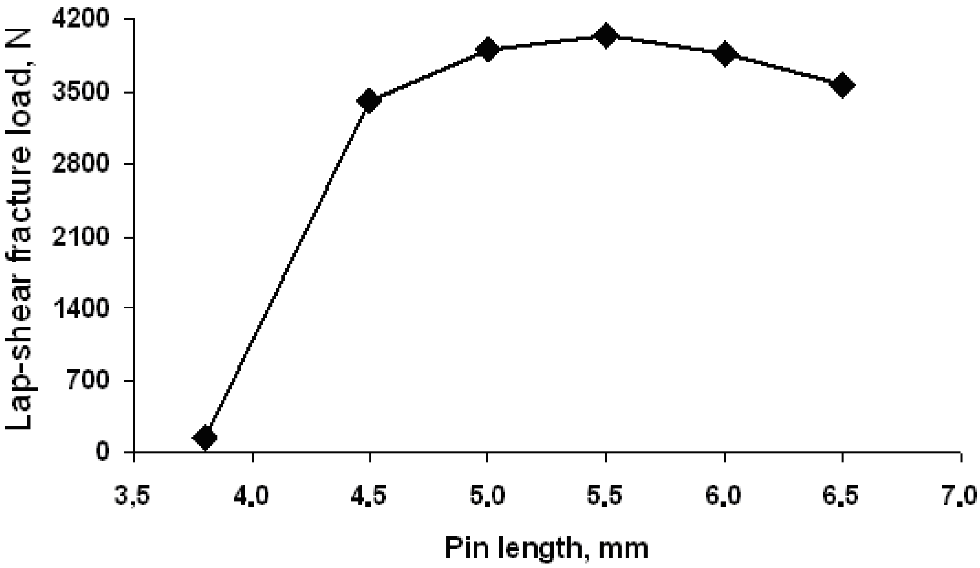

Figure 10: The effect of the pin length on the lap-shear fracture load of PP welds.

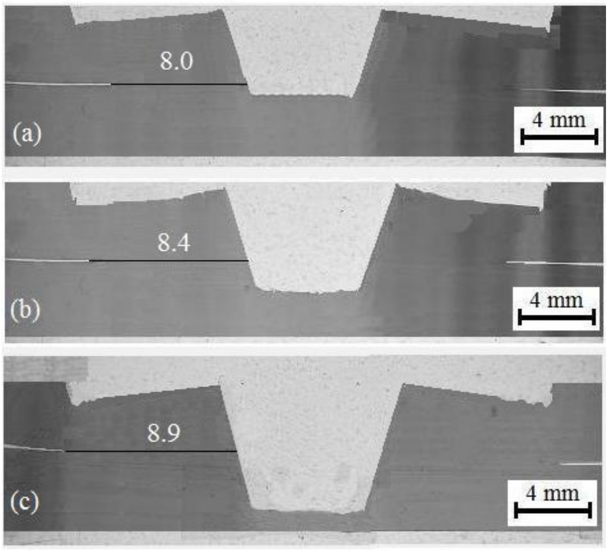

Figure 11: The effect of the pin length on the weld cross sections of PP welds (a) 4.5 mm pin length, (b) 5.5 mm pin length and (c) 6.5 mm pin length.

Figure 12: The effect of pin length on the thickness of the upper sheet of HDPE welds(a) 5.5 mm pin length and (b) 6.5 mm pin length.

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