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Pin Profile and Shoulder Geometry Effects in Friction Stir Spot Welded Polymer Sheets

Mustafa Kemal Bilici[1], Ahmet Irfan Yükler[2], Memduh Kurtulmuş[1]
[1]Marmara University Applied Science High School, Goztepe Campus, Istanbul, 34722
[2]Marmara University Technology Faculty, Goztepe Campus, Istanbul, 34722, TURKEY

ABSTRACT
The effects pin profile and shoulder geometry in friction stir spot welded polymer sheets were studied. Six different tool pin geometries were testedin friction stir spot welding(FSSW). The effects of tool shoulder diameter and shoulder cavity angle were also investigated. In the tests 4 mm thick high density polyethylene (HDPE) and polypropylene (PP) were used. All the welding operations were done at the room temperature. Lap-shear tensile tests were carried out to find the weld static strength. Weld cross section appearance observations were also examined. From the experiments the effect of pin profile and shoulder geometry on friction stir spot weld formation and weld strength were determined. The tapered cylindrical pin was found the optimum pin profile. 30 mm shoulder diameter and 6o shoulder cavity angle gave the best results.
Keywords: *Friction stir spot welding of polymers, FSSW welding tool, FSSW welding tool geometry*

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I. 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.

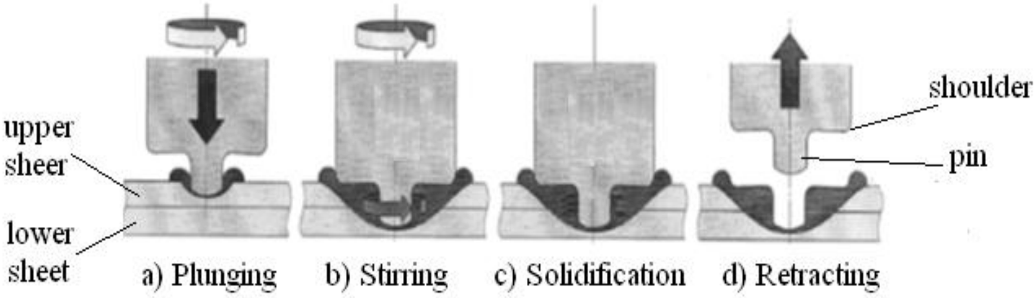

Figure 1: Four phases of friction stir spot welding process:
(a) plunging, **(b)** stirring, **(c)** solidifying and **(d)** retracting [3].

During FSSW the heat is generated at the interface of rotating tool and the work piece due to friction. The tool geometry and welding parameters effect 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].

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].

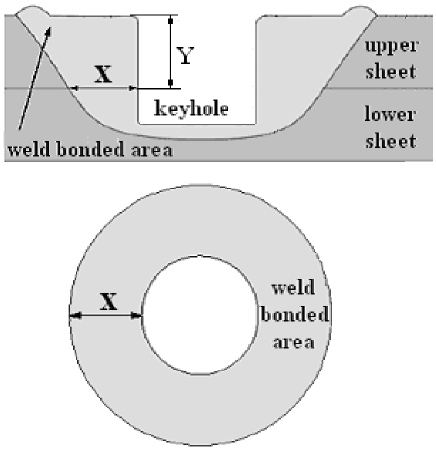

Figure 2 (a) Schematic illustration of the cross section of a friction stir spot weld; **(b)**, geometry of the weld bond area [4]: X, nugget thickness; Y, the thickness of the upper sheet [14].

In this study we intended to investigate the effects of welding tool 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, the tool shoulder diameter and the shoulder angle on weld nugget formation and the weld strength.

II. EXPERIMENTAL PROCEDURES

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. Six different tool pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular, square and hexagonal) were used to fabricate the joints (Figure 4). Each tool has a 5.5 mm pin length and 7.5 mm pin size. The tapered pin had a 15^o pin angle. In straight cylindrical, tapered cylindrical and threaded cylindrical pins, the pin size was determined by measuring the bottom diameter of the pin.The threaded cylindrical pin was produced by a standard M8 thread cylindrical pin was formed and then, the pin of the tool was milled to a 7.5 mm diameter. In triangular, square and hexagonal pins, the pin size was determined by calculating the diameter of the cross section area that was formed by the turning pin. 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 were 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 lap shear test specimens were produced. Five of them were mechanically tested and the sixth one was metallographically examined. The axial load of the six different welding tools were measured using a KISTLER 9443B dynamometer platform and a KISTLER 5019B amplifier, which was coupled with a data acquisition system so that axial force outputs during spot welding were logged on a desktop computer.

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 μm) 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		6 types
Shoulder diameter	millimeter (mm)	15-35
Shoulder concavity angle	degrees	0-12

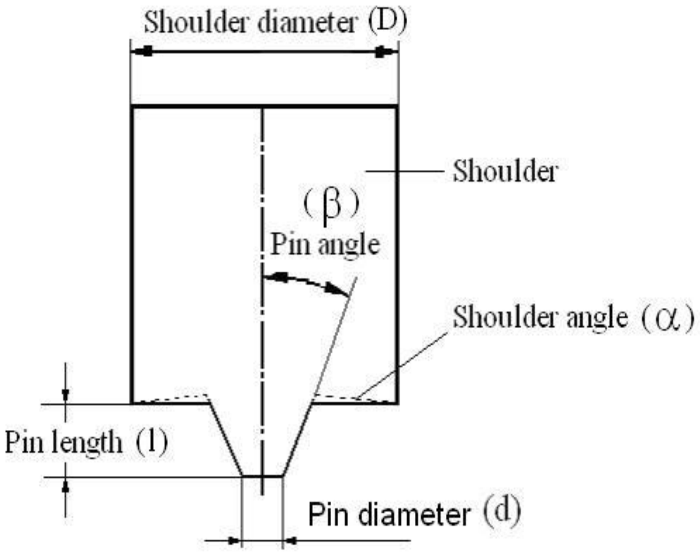

Figure 3: Friction stir spot welding tool design showing geometric parameters.

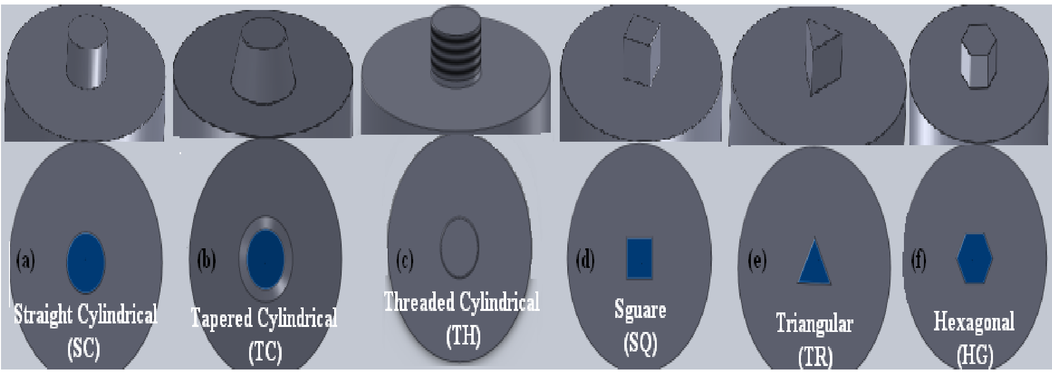

Figure 4: FSSW tool profile and pin size (d): **(a)** straight cylindrical, **(b)** tapered cylindrical **(c)** threaded cylindrical, **(d)** square, **(e)** triangular and **(f)** hexagonal.

III. RESULTS AND DISCUSSIONS

A vertical force is created in the tool during the plunging and stirring phases of the welding operation. This vertical force is called the welding force [22]. The welding force of the 7.50 mm diameter straight cylindrical pin, the 7.50 mm tapered cylindrical pin, 7.50 mm threaded cylindrical pin and. 7.5 mm diagonal length square pin was shown in Figure 5. The force was zero before the tool plunged into the upper sheet. The force increased with the plunging of the tool as shown in Figure 5. Then, the force decreased with the stirring phase and the retracting phase. The maximum load was obtained at the end of the plunging period. The maximum load was 3850 N for the straight cylindrical pin, 4775 N for the tapered cylindrical pin, 3120 N for the threaded cylindrical pin and 2160 N for the square pin. The tapered cylindrical pin gave the biggest welding force therefore, the highest friction heat generated with this pin. 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]. In the stirring phase, the temperature of the material in the vicinity of the pin increases and the friction coefficient of the material decreases [14], and thus the welding force decreases [22]. Both pins showed a decrease in welding force during the stirring period. The welding force became zero with the end of the dwell time (Figure 5).

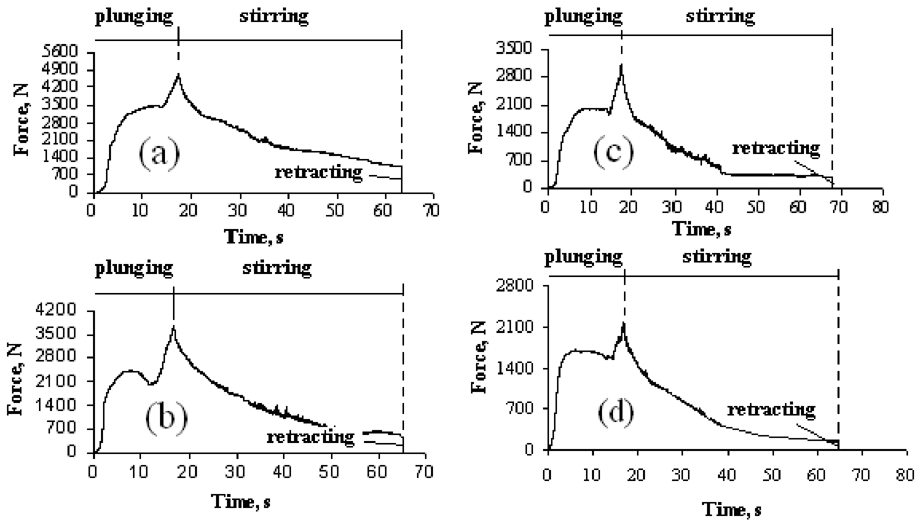

Figure 5: Welding force of HDPE sheets **(a)** the tapered cylindrical pin, **(b)** the straight cylindrical pin **(c)** the threaded cylindrical pin and **(d)** the square pin.

The effect of the tool pin profile on weld strength of HDPE welds was shown in Figure 6. 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 7. 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 8.

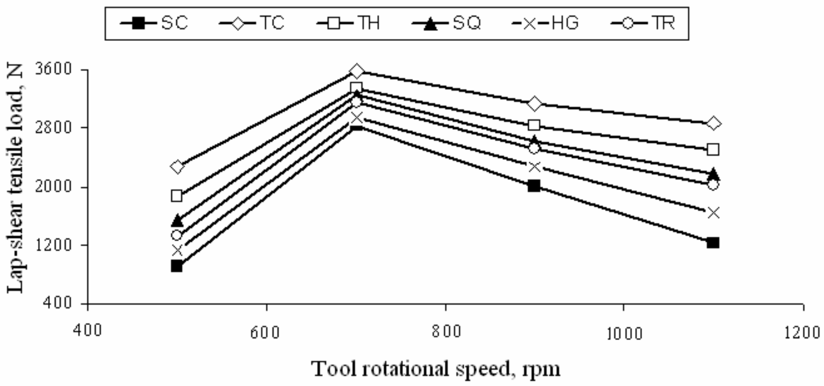

Figure 6: The effect of the tool pin profile on weld strength of HDPE welds.

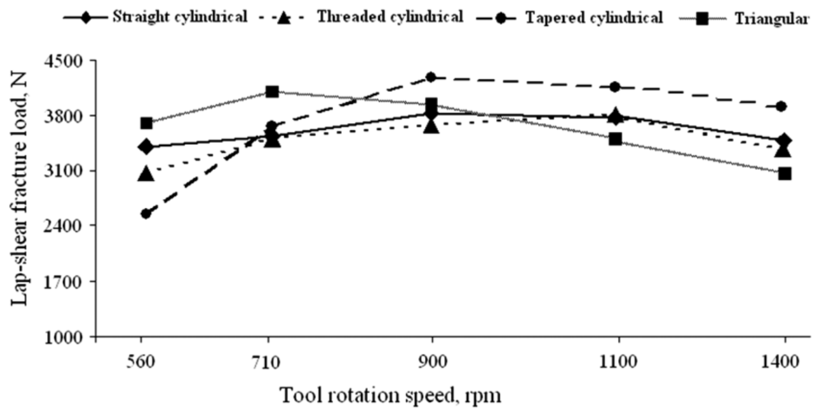

Figure 7: The effect of the tool pin profile on weld strength of PP welds.

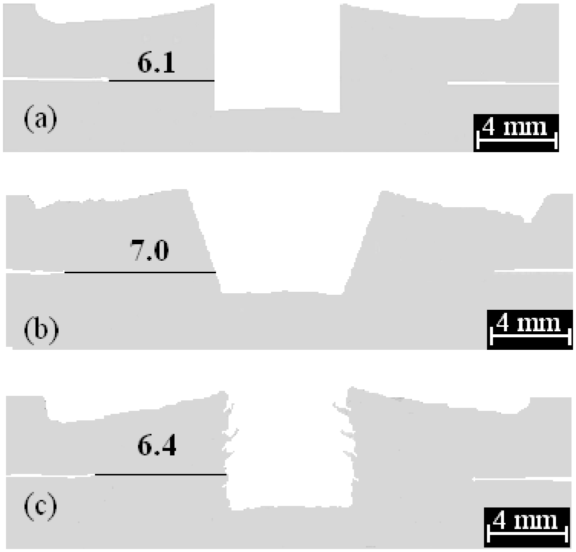

Figure 8 Effect of pin angle on weld nugget formation HDPE welds **(a)** straight cylindrical pin, **(b)** 15^o pin angled tapered cylindrical pin and **(c)** threaded straight cylindrical pin.

The nugget thickness of the straight cylindrical is 6.1 mm, the nugget 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 pin as 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 9 illustrates the effect of the shoulder diameter on the lap-shear fracture load and Figure 10 illustrates the nugget formation in PP welds. Figure 11 illustrates the effect of the shoulder diameter on the lap-shear fracture load and Figure 12 illustrates the nugget formation in HDPE welds. Tapered cylindrical pin geometry used in these welds. All the tools had a 6^o shoulder cavity angle, 15° pin angle, 7.5 mm pin diameter and 5.5 mm pin length. The shoulder diameter was varied between 10 and 35 mm. In both polymers the lap-shear tensile force increased with the shoulder diameter up to 30 mm.The fracture load increased with the shoulder diameter up to 30 mm diameter, because more friction heat[13] and a bigger nugget thickness[26] was produced as shown in Figure 10 and 12. The best facture load was obtained with the 30 mm shoulder diameter. Then the lap-shear fracture load reduced slightly with the increased shoulder diameter. In polymer FSSW friction heat generated at the vicinity of the pin and under the tool shoulder [23,25]. The heat generated by the shoulder increases with the shoulder diameter[25]. If the shoulder diameter enormously enlarges excessive heat generates and the nugget thickness increases. But this increase doesn’t bring a benefit in weld strength.The reason of the strength decrease was due to the chain scission [27]. Chain scission lowers the strength of a thermoplastic material [28]. If a molten 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 [27]. The mechanical properties of thermoplastics decrease with lowering the molecular weight [29]. In FSSW the welding tool produces a compressive pressure in the weld zone [30]. In FSSW of thermoplastics the material in the weld area melts [3]. Very high temperatures were recorded in FSW of plastics [31,32]. High melt temperatures and high welding forces cause chain scission in the welding zone of the plastics which lowers the weld strength [33].

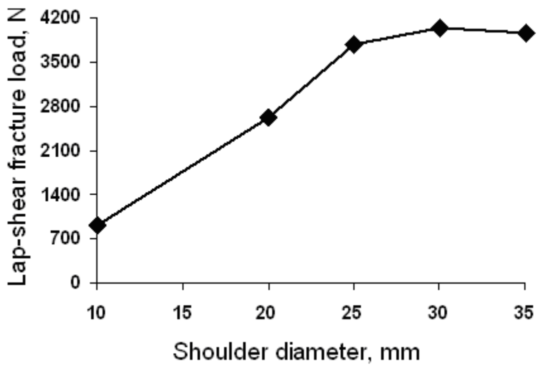

Figure 9: Effect of tool shoulder diameter on weld strength of PP welds which were welded with the same welding parameters.

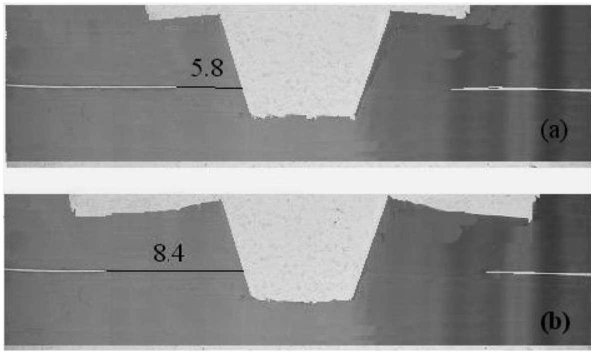

Figure 10: The effect of the shoulder diameter on the weld cross sections of PP welds which were welded with the same welding parameters **(a)** 20 mm shoulder diameter and **(b)** 30 mm shoulder diameter.

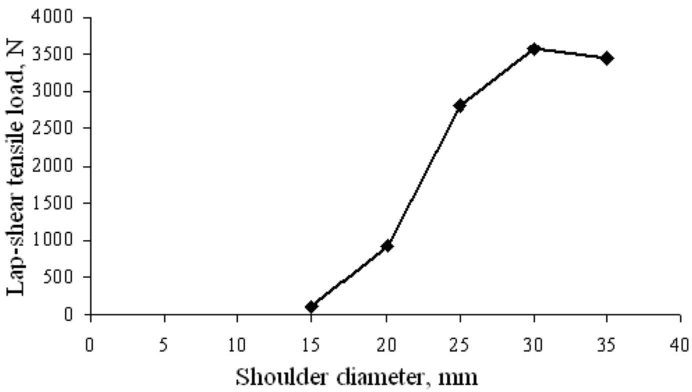

Figure 11: Effect of tool shoulder diameter on weld strength of HDPE welds which were welded with the same welding parameters.

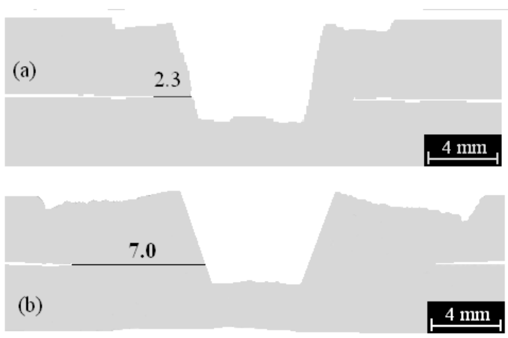

Figure 12: Effect of the shoulder diameter on the joint cross section of HDPE welds which were welded with the same welding parameters **(a)** 15 mm shoulder diameter tool and **(b)** 30 mm shoulder diameter tool.

The effect of the shoulder concavity angle on the weld strength of PP welds was shown in Figure 13 and HDPE welds was shown in Figure 14. The effect of shoulder concavity angle on HDPE weld nugget formation is shown in Fig. 15. In these welds the tool had a 30 mm shoulder diameter, 15° pin angle, 7.5 mm pin diameter and 5.5 mm pin length. The nugget thickness was 0.4 mm for 0^o shoulder concavity angle, and the nugget thickness was 2.5 mm for 3^oshoulder concavity angle and 6.7 mm for the 6^oshoulder concavity angle(Figure 15). When the shoulder concavity angle is 0o, liquid material was expelled out. Therefore, the weld strength was very low(Figure 13 and 14).The fracture load increased with the shoulder angle. The best load was obtained with the 6° shoulder angle. Increasing the shoulder angle beyond the 6° angle the weld strength decreased. More friction hear was generated with bigger shoulder cavity which caused chain scission and strength loose.

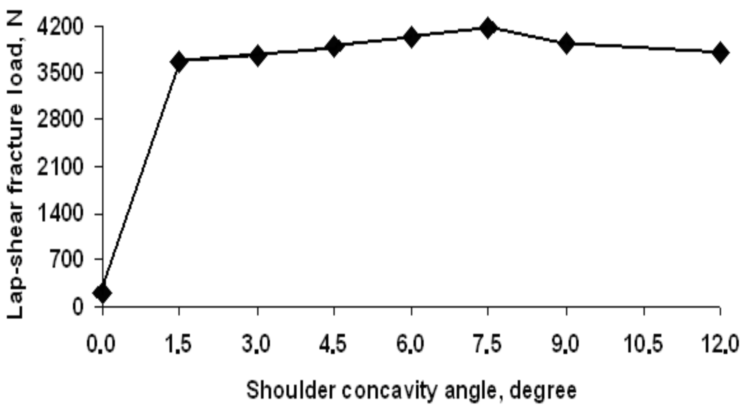

Figure 13: The effect of the shoulder angle on the lap-shear fracture load of PP welds.

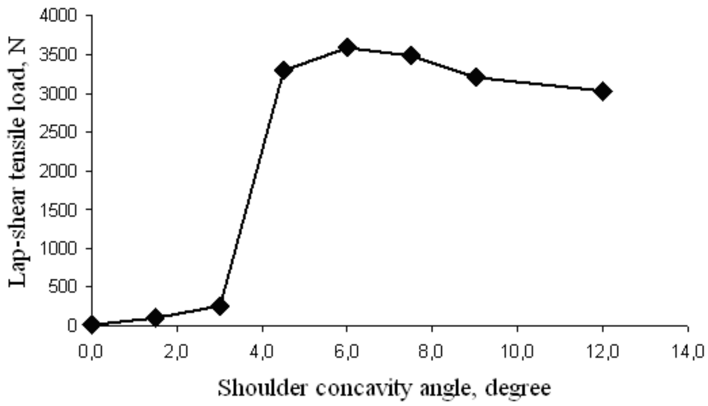

Figure 14: Effect of shoulder concavity angle on lap-shear fracture load of HDPE welds.

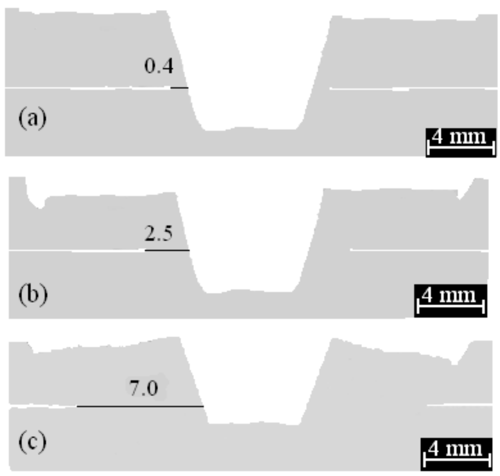

Figure 15: Effect of the shoulder concavity angle on the joint cross section: (a) 0^oshoulder concavity angle and (b) 3 ^{o}shoulder concavity angle and 6 ^{o} shoulder concavity angle.

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