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The Effects of Critical Welding Parameters on Tensile-Shear Properties of Friction Stir Spot Welded Polyethylene

Araştırma Makalesi / Research Article

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ABSTRACT

The aim of this study was to investigate the weldability of high density polyethylene via friction stir spot welding method. Polyethylene sheets were joined with dwell times of 60 to 100 s, three different pin profiles (M6×1, M6×1.25, M6×1.5) and pin lengths of 3.75 to 4.75 mm by using rotational speed of 900 rpm and delay time of 45 s. During welding processes, the temperatures were measured under the welding centers. The tensile-shear tests were performed to welded samples. Also, macrostructures of welding nuggets were examined. The small welding nuggets were formed by using the lower dwell time. The melting in welding nugget occurred in the all dwell times during the welding. The dwell time affected on the friction temperature. The key (pin) hole closed when sufficient friction temperature (dwell times of 80 and 100 s). The pin profiles directly affected the welding quality. Large screw pitch range of the pin and the small pin length from 4.5 mm negatively affected the weld fracture load. Pin length of the stirring tool directly affected the quality of welding.

Keywords: FSSW, polyethylene, welding parameters, tensile-shear properties.

ÖZ

Bu çalışmanın amacı, sürtünme karıştırma nokta kaynak yöntemi ile yüksek yoğunluklu polietilen malzemelerin kaynaklanabilirliğini araştırmaktır. Polietilen levhalar, 900 dev/dak devir sayısı ve 45 s bekleme süresi kullanılarak, 60-100 s karıştırma süresi, üç farklı pim profile (M6×1, M6×1.25, M6×1.5) ve 3.75-4.75 mm pim uzunluklarında birleştirilmiştir. Kaynak işlemi esnasında kaynak merkezinin altından sıcaklık ölçümleri yapılmıştır. Kaynaklı numunelere çekmek-kayma testleri uygulanmıştır. Ayrıca kaynak çekirdeklerinin makro görüntüleri incelenmiştir. Düşük karıştırma süreleri kullanıldığında küçük kaynak çekirdekleri oluşmuştur. Tüm karıştırma sürelerinde kaynak çekirdeğinde ergime meydana gelmiştir. Karıştırma süresi sürtünme sıcaklığına etki etmiştir. Yeterli sürtünme sıcaklığı (80 ve 100 s) oluştuğunda kaynak çekirdeğindeki anahtar (pim) değili kapanmıştır. Pim profili kaynak kalitesine doğrudan etki etmiştir. Büyük adımlı vidalı olan pim ve 4.5 mm'den küçük pim boyları kaynak kopma mukavemetini olumsuz etkilemiştir. Karıştırıcı takımın pim boyunun kaynak kalitesine doğrudan etki ettiği belirlenmiştir.

Anahtar Kelimeler: SKNK, polietilen, kaynak parametreleri, çekme-kayma özellikleri.

1. INTRODUCTION

Recently, polymer materials have increasingly been replacing wood materials, metals and its alloys in different industrial fields (automotive, aerospace, ship, building, furniture, medical, food storage etc.).With use of polymers has resulted in remarkable cost efficiency increases for the industries. Besides production cost, polymeric materials present many advantages such as weight saving, flexibility and thermal insulation [1-4]. Also, in the aerospace and automotive industries, the use of polymers and polymer matrix composites [3] has recently increased for fuel efficiency. For other consumer products, such as mobile phones [1], various electrical devices [4], computers, building and household appliances [3], the rapid spreading of polymer materials has provided many advantages [1,2,6].

The welding is one of the most important manufacturing methods that is commonly used. The welding of polymeric materials plays an ever increasing importance in today's various industrial fields [7-9]. Polymer welds are present in various applications in the industrial fields including electronics, packaging, automotive, building, medical devices etc [7]. The welding technologies is constantly improving itself [7,8]. The weld is considered one of the most critical steps in manufacturing; hence a better understanding is required. Also, from a scientific point of view, weldability of polymeric materials and weld strength establishment is of importance [7-11].

Polymers are welded various welding methods such as hot plate, laser, vibration, ultrasonic, friction, friction stir welding (FSW) etc [1]. One of these methods is Friction Stir Spot Welding (FSSW) that is discovered by Mazda Motor Company in 1993 [7,12,13]. FSSW was developed

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in the automotive industry as an alternative for electrical resistance spot welding (RSW) of Al alloys. RSW is a welding method that can only be applied to a limited material that can form resistance. With FSSW, ferrous, non-ferrous metals and also numerous polymers can weld. It can only be applied as a spot welding on overlapping type materials. The method that was started to be used in the joining of aluminum alloys used in automotive industry in 2001, attracts attention in the other industry branches [14-18].

There are very few publications on polymers FSSW applications. Juhl studied polystyrene laser welds. He reported this method was very good for testing weld strength where chain pullouts were the dominating fracture mechanism [7]. Bilici studied the effect of tool geometry on FSSW of polypropylene. He reported that the tool geometry in FSSW affects stir zone formation and weld fracture load [19]. Dashatan studied FSSW of dissimilar polymethyl methacrylate and acrylonitrile butadiene styrene sheets. He investigated the effects of rotational speed, tool plunge rate and dwell time on fraction load of welded sample. He reported that the parameters dramatically affected the weld fraction load. Also, the most effective parameter was found to be tool plunge rate [20]. Arici studied FSSW of polypropylene. He investigated the effects of tool penetration depth and dwell time on joint strength of welded polypropylene in the publication. He reported that increasing the dwell time causes a significant improvement on weld fracture load but there is an optimal point for tool penetration [21].

In this study, FSSW was performed to join HDPE sheets in order to understand the effect of the dwell time, pin profile and pin length on welded joints. The characteristics of the macrostructural of welded joints were investigated. Also, the tensile-shear tests were performed to welded joints and were determined mechanical strength of welded samples.

2. EXPERIMENTAL

2.1. Materials

The high density polyethylene (HDPE) sheets were utilized in this study and this material was in white color. HDPE has some feature, such as low cost, light-weight, flexibility, formability and good mechanical properties. The material which has a board spectrum of applications, such as in the chemical, automotive and the other industries [2]. Samples were cut in 30×100 mm size of 3 mm thickness. Some characteristics of polyethylene material are given in Table 1.

2.2. Stirring Tool Properties

For FSSW processes, a stirring tool was designed and manufactured by X210Cr12 steel in a modular structure (Figure 1). The shoulder diameter was 20 mm. Straight cylindrical screw pin profiles (M6×1, M6×1.25, M6×1.5) were used to fabricate the joints. The hardness of shoulder and pins were obtained after 50 HR_C through heat treatment applied. Figure 1 shows the shoulder and pins.

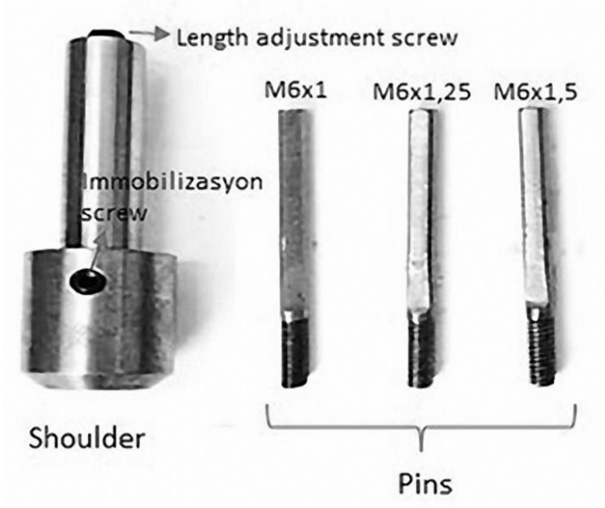

Figure 1. Stirring tool (shoulder and pins)

2.3. Method

Before welding processes; HDPE sheets were fixed in the form of overlapping. The rotational direction of the stirring tool was selected as clockwise. The stirring tool was immersed in the polyethylene sheets at 1 mm constant shoulder immersing depth. FSSW processes were performed at rotational speed of 900 rpm with constant delay time of 45 seconds, dwell time of 60, 80, and 100 seconds, three different straight cylindrical threaded pin profiles which has 1, 1.25 and 1.5 mm pitch ranges, and five different pin lengths between 3.75 and 4.75 mm with 0.25 mm intervals. Milling machine was used for FSSW. During the welding process, the chances of temperature were measured with digital K type thermocouple (Cr-Ni). The weld samples were described; dwell time (DW), screw pitch (pin profile) (P) and pin length (L). Therefore, the designation DW60P1L4.5 corresponds to a weld carried out with a dwell time of 60 (s), a pin profile of 1 (mm) and pin length of 4.5 (mm). Macrostructure analyses were carried out using a photograph machine. Tensile-shear test was applied to the welded polyethylene sheets. Tensile-shear test was

Table 1. The properties of the polyethylene

Tensile strength (MPa)	Strain at break (%)	Modulus of Elasticity (MPa)	Density (gr/cm^3)	Melting temperature (ºC)	Coefficient of friction
~32	~50	800	0,95	135	0,3

performed at 10 mm·min^{-1} speed by using a microcomputer controlled electronic test machine. By examining the data obtained; the effect of the welding parameters (dwell time, pin profile, and pin length) on the mechanical performance of the welded joints was analyzed. Figure 2 shows image of the sample joined by using FSSW method.

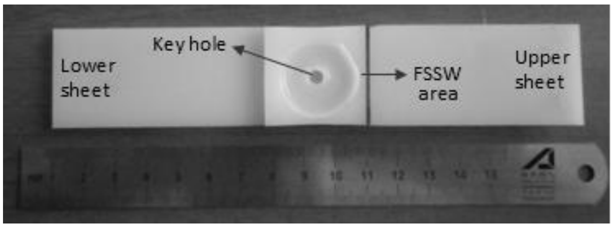

Figure 2. Friction stir spot welded sample

3. RESULTS AND DISCUSSION

3.1. Temperature Measurement

Figure 3 shows effect of dwell time on friction temperature in the samples of DW60P1L4.5, DW80P1L4.5, and DW100P1L4.5. When Figure 3 was examined, it was observed that temperatures measured in the weld centre increased with the dwell time. Temperature was measured as 162^{o}C in dwell time of 60 s, 184^{o}C in 80 s, and 201^{o}C in 100 s. As the dwell time increased, the stirring tool had more friction on surfaces of joined sheets. This situation caused an increase in friction temperature. The melting temperature of the polyethylene material was approximately 135^{o}C [2]. Considering the melting temperature of the joined material; the melting occurred in the weld zones in all of these three dwell times. It is clear seen from the Figure 3 that the FSSW method, which is the solid state welding in metals, caused the melting in polyethylene.

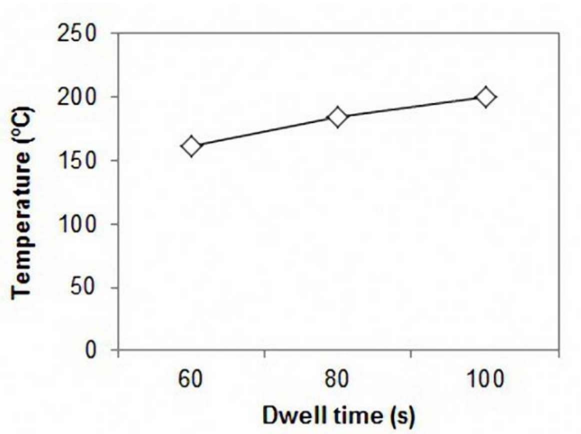

Figure 3. Effect of dwell time on friction temperature

3.2. Macrostructre Analysis

Figure 4 shows upper surface macrostructure of weld nugget FSSWed polyethylene sheets. Figure 5 shows cross-sectional macrostructures of weld nugget. As the dwell time increased, the friction temperature increased in weld zone and the spot weld nugget expanded. Key (pin) hole formed in the weld nugget in low dwell time (DW60P1L4.5). As the dwell time increased (DW80P1L4.5, DW100P1L4.5), the hole where the pin exited was closed extensionally. In case that the hole where the pin exits was closed, cross sectional area of the welding nugget enlarged on the plane to which the polyethylene materials contacted (Figure 5). In overlapping type joints, enlargement of the weld nugget area affected the mechanical performance positively [14, 15, 19]. Polyethylene material, molten met due to effect of inertia forces caused by stirring tool during high dwell time, was taken outside weld nugget and formed a cordon. Moreover, formation of void defects was observed in the joints performed in dwell times of 80 s and 100 s (DW80P1L4.5, DW100P1L4.5) (Figure 5.b and c). Dwell time in FSSW process affected macrostructure of the weld. Dashatan reported that the dwell time dramatically affected the weld morphology and tensile shear strength [20]. Arici and Mert [21] and Bilici et al. [22] reported that increasing dwell time caused a significant improvement on weld morphology, strength, and fracture mode.

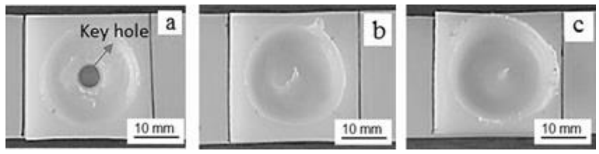

Figure 4. Effect of dwell time on the macrostructure of the spot weld nugget, a) DW60P1L4.5, b) DW80P1L4.5, c) DW100P1L4.5

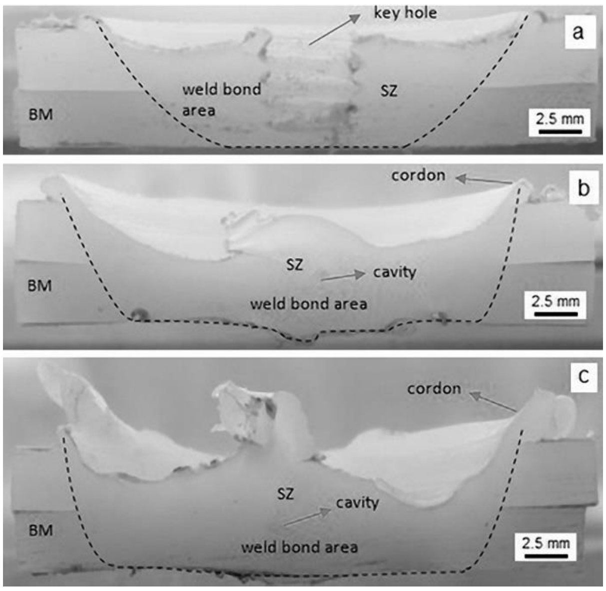

Figure 5. The cross-sectional macrostructures of welds performed with increasing dwell time, a) DW60P1L4.5, b) DW80P1L4.5, c) DW100P1L4.5 (BM: Base Metal, SZ: Stir Zone)

3.3. Tensile-Shear Tests Results

The weld quality of a spot weld is usually defined by its superior mechanical properties. Therefore, the quality of the FSSW joint can also be defined by its high mechanical strength [20]. The results of tensile-shear tests of welded samples are presented in Table 2.

Table 2. Results of tensile-shear tests

Dwell time (s)	Pin profile	Pin length (mm)	Fracture load (N)
60	M6×1	3.75	174.8
		4	472.7
		4.25	955.6
		4.5	1253
		4.75	1395.1
	M6×1.25	3.75	142.6
		4	508.3
		4.25	927.4
		4.5	1201.4
		4.75	1308
	M6×1.5	3.75	113.2
		4	341.2
		4.25	648.3
		4.5	1198.2
		4.75	1268.9
80	M6×1	3.75	235.4
		4	568.06
		4.25	1337.1
		4.5	1587
		4.75	1671.3
	M6×1.25	3.75	208.3
		4	534.7
		4.25	1295
		4.5	1644
		4.75	1649.4
	M6×1.5	3.75	167.3
		4	524.1
		4.25	1192.6
		4.5	1411.5
		4.75	1483.7
100	M6×1	3.75	329.2
		4	809.8
		4.25	1429.7
		4.5	1636.8
		4.75	1807.2
	M6×1.25	3.75	306.8
		4	977
		4.25	1451.6
		4.5	1603
		4.75	1771.2
	M6×1.5	3.75	189.1
		4	642.9
		4.25	1181.4
		4.5	1563
		4.75	1681.9

3.4. Effect Of Welding Parameters On Tensile-Shear Strength

Figure 6 shows effects of dwell time in samples joined with a pin profile of M6×1 on tensile shear strength. The tensile-shear test results of the welded samples joined with a pin length of 4.75 were used in graphic. When the graphic was examined, weld fracture loads significantly increased with increasing dwell time. Low fracture load (1395.1 N) was obtained since inadequate friction temperature occurred in the joint (DW60P1L4.75) welded in the dwell time of 60 s by using a pin profile of M6×1. When dwell times were chosen as 80 s and 100 s (DW80P1L4.75, DW100P1L4.75), fracture loads increased up to 19% and 30%, respectively. As dwell time extended, friction temperature increased, diameter of spot welding nuggets increased and joints having better quality were achieved. Spot welding with low penetration and a nugget diameter of ~13 mm occurred in dwell time of 60 s. Moreover, a key hole formed in spot welding nugget. On the other hand, spot welding with higher penetration and a nugget diameter of ~17 mm occurred in dwell time of 80 s. When dwell time was kept high (100 s), the hole where the pin exited was closed and a larger weld nugget with adequate penetration (in a diameter of ~20 mm) formed. It was observed that dwell time was an effective parameter on welding rupture force and affected the mechanical performance of the joints positively [15,19,20].

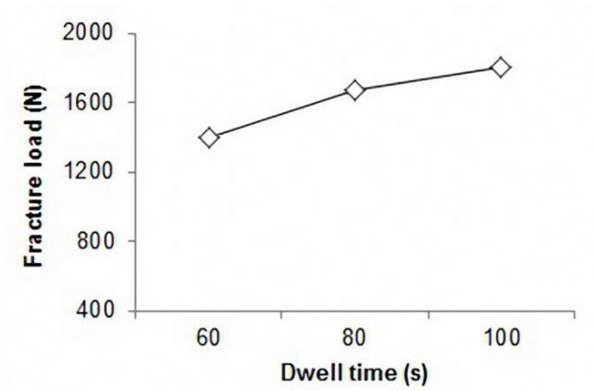

Figure 6. Effect of dwell time on fracture load

Figure 7 illustrates fracture modes of the welded samples which were joined in the pin profile of M6×1 by using different dwell times. Cross nugget fracture mode occurred in the samples (DW60P1L4.75, DW80P1L4.75) welded in dwell times of 60 s and 80 s [20,21]. In samples with this type of fracture mode, the weld nugget was cut and upper sheet and lower sheet were completely separated from each other. When dwell time was kept high (100 s), the hole where the pin exited was closed and a larger weld nugget with adequate penetration formed. Upper sheet fracture mode [20-22] was observed in the welded joints (DW100P1L4.75) in which the dwell time of 100 s was used (Figure 7.a). In DW100P1L4.75 sample, fracture occurred in interface of weld nugget-base material (Figure 7.b) The best welding quality among the whole samples was achieved in the sample (DW100P1L4.75) joined by using a dwell time of 100 s (Figure 7.c).

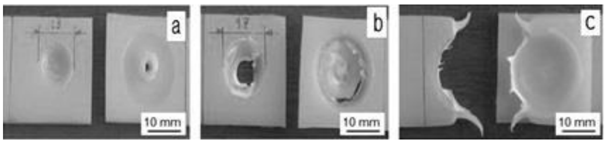

Figure 7. Effect of dwell time on macroscopic fracture mode, a) DW60P1L4.75, b) DW80P1L4.75, c) DW100P1L4.75

Figure 8 illustrates the effect of pin profile on fracture load. The tensile-shear test results of the welded samples (DW100P1L4.75, DW100P1.25L4.75, DW100P1.5L4.75) joined with a pin length of 4.75 mm in the dwell time of 100 s were used in graphic. When the graphic was examined; it was observed that fracture loads decreased as screw pitch increased. Fracture load of 1807.2 N was obtained in the welded joint (DW100P1L4.75) performed in the dwell time of 100 s by using the pin profile of M6×1. Fracture loads obtained in DW100P1.25L4.75 and DW100P1.5L4.75 samples were determined as 1771.2 and 1681.9, respectively. As the screw pitch increased, a decrease up to 7% was observed in fracture load. Furthermore, a material loss occurred in the weld zone by the increase in screw pitch. Task of pin in FSSW process is to stir homogeneously the polyethylene material which softens in the weld zone [19-22]. Screw threaded pins stirred the softened material at the high rotational speed and transferred it inside screw pitches. As screw pitch increased, more material was transferred. Softened material, which was transferred, was moved outside the stir tool by the effect of rotation at high rotational speed and formed a cordon around the weld nugget. This situation led to decrease the cross-sectional area of the weld. The decrease in cross-sectional area of welding seam reduced the fracture load. Figure 9 illustrates fracture modes of the welded samples which were joined in different pin profiles in the dwell time of 100 s. When dwell time was kept high, the hole from which pin existed was closed in all of pin profiles and a larger weld nugget formed. Upper sheet fracture mode [20-22] was observed in the welded joints (Figure 9.a-c). Fractures occurred in interface of weld nugget-base material. The best welding quality was obtained with a pin having a screw pitch of 1 mm (M6×1).

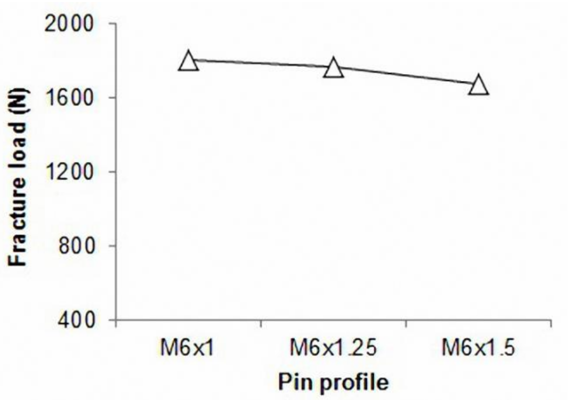

Figure 8. Effect of pin profile on fracture load

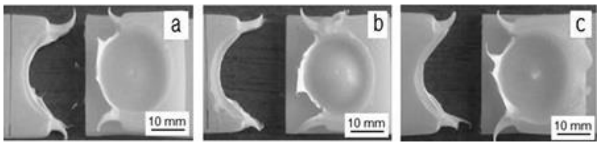

Figure 9. Effect of pin profile on macroscopic fracture mode, a) DW100P1L4.75, b) DW100P1.25L4.75, c) DW100P1.5L4.75

Table 2 illustrates the effect of pin length on tensile-shear test results. Pin length affected mechanical properties of the joint in FSSW process. As pin length increased in all of rotational speeds and all of pin profiles, fracture load increased. Figure 10 illustrates the relationship between pin length and fracture load. The results of tensile-shear test of the welded samples joined with a pin profile of M6×1.25 in the dwell time of 60 s were used in graphic in Figure 10. When the graphic was examined, fracture loads increased significantly with increasing pin length. Fracture load was obtained as 142.6 N in DW60P1.25L3.75 sample and 508.3 N in DW60P1.25L4 sample. Poor welding joint formed in these samples. Fracture load of 927.4 N was obtained in DW60P1.25L4.25 sample. Since stirring remained inadequate also in the pin length of 4.25 mm, the welding quality was slightly poor than good. Fracture load of 1201.4 N was determined in DW60P1.25L4.25 sample joined with the pin length of 4.5 mm. Good welding quality was obtained since depth of stirring was more. When pin length was chosen as 4.75 mm, the highest fracture load (1308 N) was determined in DW60P1.25L4.75 sample. The best welding quality was achieved with the pin length of 4.75 mm for this experimental group.

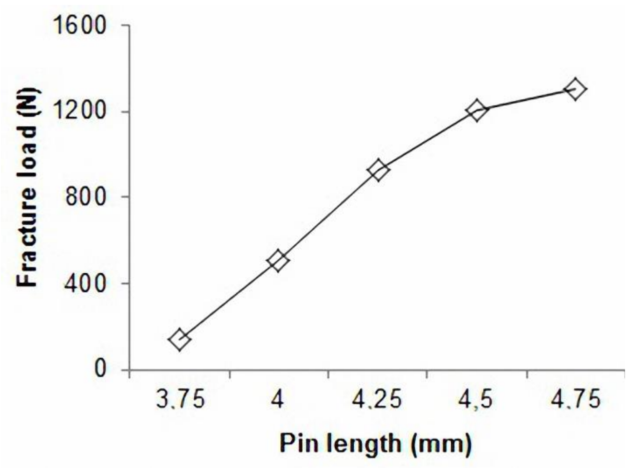

Figure 10. Effect of pin length on fracture load

Figure 11 illustrates fracture modes of the welded samples joined by using different dwell times in the pin profile of M6×1. Nugget put-out fracture mode was observed in the pin length of 3.75 mm. Upper sheet was completely separated from lower sheet in the samples with nugget pull-out fracture mode due to the effect of inadequate penetration (Figure 11.a). Cross nugget fracture mode [20] was observed in the pin length of 4.5 mm (Figure 11.b). When the pin length was 4.75 mm, upper sheet fracture mode [20] was observed since the weld nugget had deeper penetration. Upper sheet fracture mode occurred in interface of weld nugget-base material (Figure 11.c).

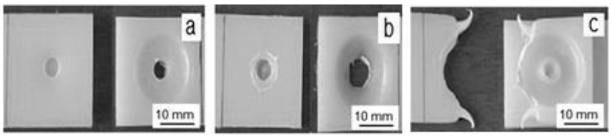

Figure 11. Effect of pin length on macroscopic fracture mode, a) DW60P1.25L3.75, b) DW60P1.25L4.25, c) DW60P1.25L4.75

4. CONCLUSIONS

Polyethylene material sheets were joined by using friction stir spot welding in the present study and the results obtained can be summarized in general as follows:

1. Heat input increased in the weld zone with increasing dwell time.
2. Polyethylene sheets melted locally in all of dwell times. During welding, it is required that weld zone is exposed to high heat for sufficient time so that chain molecules in the structure of polymer are broken and chemical degradation occurs.
3. Key hole, from which pin was formed, closed extensionally in dwell times of 80 s and 100 s. When pin hole closed, cross-sectional area of the weld nugget expanded in the plane to which polyethylene sheets contacted.
4. Enlargement of area of welding seam affected mechanical performance positively.
5. Dwell time affected fracture load. Fracture loads increased with increasing dwell time.
6. Selection of stirring tool with proper design directly affects the welding quality. Threaded pin profile with large pitch affected the fracture load negatively. Therefore, it is recommended to join the polyethylene sheets with using threaded pin which has small picth.
7. Pin length of the stirring tool is one of the most important parameters that affect the welding quality. As the pin length increased, the fracture loads increased. Low-strength welded joints were obtained in short pin length due to inadequate stirring and penetration.
8. It was observed that different fracture modes occurred in the welded joints; the nugget pull-out fracture mode, cross nugget fracture mode, and upper sheet fracture mode.

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