International Journal of the Physical Sciences Vol. 7(4), pp. 647 - 654, 23 January, 2012
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.1653
ISSN 1992 - 1950 ©2012 Academic Journals

Full Length Research Paper

A study on the role of processing parameters in joining polyethylene sheets via heat assisted friction stir welding: Investigating microstructure, tensile and flexural properties

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Accepted 15 December, 2011

The aim of this study was to investigate the weldability of high-density polyethylene sheets via heat assisted friction stir welding and effect of process parameters on microstructure and mechanical properties of welded plates. The parameters under study were included pin rotational speed, transverse speed of tool and shoulder temperature. Tensile and bend tests were done in order to evaluate mechanical behavior of material. The results showed that polyethylene plates could be welded with joint characteristics similar to base material. This could be accomplished by operating with a high shoulder temperature and rotational speed as well as low transverse speed. Moreover, when process parameters were properly selected to provide sufficient heat, the weld nugget would extend to base material. Consequently, a remarkable improvement was observed in joint efficiency. Also, based on microstructure observations and mechanical test results, it could be concluded that, tool coating improved mechanical properties and surface quality of weld.

Key words: Friction stir welding, polyethylene, mechanical properties, microstructure.

INTRODUCTION

High-density polyethylene (HDPE) is one of the most popular polymers due to its availability and competitive cost. Furthermore, it is a thermoplastic with noticeable mechanical properties (Arbon et al., 2011). However, the need to produce larger and more complex parts from polymers such as HDPE has created an increased demand for joining. Furthermore, with the increasing development of engineering plastics, the demand for reliable, rapid, high productivity and cost effective joining methods, similar to those used in the case of metals, also increase (Kalpakjian and Schmid, 2003). In the case of creating a joint with high efficiency (the ratio of joint strength to base material strength) between currently available joining methods, welding is the best option (Kiss and Czigany, 2007; Grewell et al., 2003; Arici and Sinmaz, 2005). Plastic welding processes can be divided into two main groups: processes involving mechanical movement to produce heat (ultrasonic welding, friction welding, vibration welding) and processes involving external heating (hot plate welding, hot gas welding and resistive and implant welding) (Arici and Sinmaz, 2005). All plastic welding techniques consist of three common stages: (a) formation of a layer of molten material on the surfaces to be joined, (b) bond formation by application of pressure, (c) the melt is allowed to cool, and in this stage pressure should be maintained in order to prevent forming voids inside the weld zone (Strand, 2003). The last stage is the most significant one and an additional care should be taken to achieve a high quality weld.

Friction stir welding (FSW) produces welds by using a rotating, non-consumable welding tool to locally soften a workpiece, through heat produced by friction and plastic work, thereby allowing the tool to "stir" the joint surfaces

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Abbreviations: FSW, Friction stir welding; **PE**, polyethylene; **HDPE**, high density polyethylene.

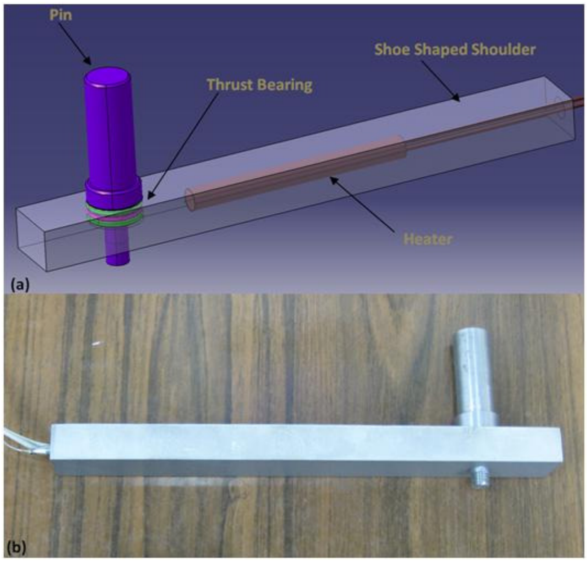

Figure 1. Picture of the designed tool for FSW of polymers. (a) Schematic illustration and (b) photograph of the tool.

(Lohwasser and Chen, 2010). This process was first developed by The Welding Institute (TWI) for joining aluminum alloys (Thomas et al., 1991; Boz and Kurt, 2004). So far, there have been immense advances in the process technology, especially in the field of weldable materials. Thus, nowadays, a wide variety of materials, such as aluminum alloys, copper and magnesium, titanium alloys and steels can be joined by this method (Bozkurt and Duman, 2011; Barlas and Uzun, 2010; Kohn et al., 1999; Ramirez and Juhas, 2003; Sato et al., 2005; Harris and Norman, 2003). Friction stir welding was applied in plastics for the first time in 1997 (Strand, 2003). Since then, several researches have been done to improve the welding quality and enhance weld efficiency in joining polymeric materials (Saeidi et al., 2009; Arici and Selale, 2007; Aydin, 2010; Rezgui et al., 2010; Troughton, 2008; Bozkurt, 2011; Squeo et al., 2009; Payganeh et al 2011). Plastic sheets joined by conventional FSW tool, which consists of an integrated pin and shoulder, presented low tensile strength (25% of base polypropylene (PP) composite strength) (Saeidi et al., 2009). Although, Arici and Selale (2007) investigated the effects of double passes of tool in FSW of polyethylene (PE) to eliminate the root defect and improve weld efficiency, the strength of welded sheet was lower than 90% of base PE tensile strength. In other work (Aydin, 2010), the effect of preheating on the FSW of ultrahigh molecular weight PE was investigated. This additional heat enabled the plastic material to be easily stirred. It was concluded that achieved weld efficiency is 89% of base material. The designed tool in Rezgui et al. (2010) study that using a low thermal conductivity scraper insulates the welded samples thereby preserve the heat gained from friction thus avoiding the appearance of blisters and split after welding. However, similar to earlier mentioned methods, achieved joint efficiency was lower than 90%. From the knowledge of the author, there is no efficient method to achieve a joint with mechanical strength higher than 95% of base material. In other words, although conventional FSW is very successful in welding metals, especially aluminum alloys, suffers from some problems when applied to plastic welding (Troughton, 2008). To remove these problems, a tool was used by Strand (2004) that consists of a rotating pin, a large shoulder and a heater for joining polypropylene sheets.

The tool used in the present study is designed based on the tooling system that has been developed (Strand, 2004). It consists of a shoe, a rotating pin and a heater, which is located at the back of the pin. The designed tool provides the mixing and joining of plastic parts together in the presence of heat. Additionally, a specially designed fixture was utilized to assure that the tool works in its best performance. The shoulder is stationary relative to pin, whereas in FSW of metals, the shoulder rotates with the pin. Furthermore, the shoulder surface was coated with PTFE. The tooling system is as shown in Figure 1. The main role of pin is to produce frictional heat for softening the workpiece and stirring material within the joint. The tool's shoulder is similar to a shoe, which is utilized to contain the displaced material and hold it on the weld, while it is cooled. A heater, equipped with a closed-loop thermo-controller, is primarily responsible for supplying additional heating for the workpiece and slowing down the cooling rate of material. The main objective of this research is to investigate the effects of process parameters, such as rotational speed of pin, tool transverse speed and adjusted heater temperature, on mechanical behavior-ultimate tensile and flexural strength and microstructure of high-density polyethylene sheets. Furthermore, the shoulder coating effects' on micro-structure and mechanical properties has been investigated.

MATERIALS AND METHODS

The materials used in this study were commercial grades. HDPE used was Rigdex HD 5218 EA supplied by Arak Petrochemical Company. The mechanical and physical properties of this material are given in Table1. Samples' thickness, width and length were 10, 100 and 200, respectively. The tool pin was made of AISI H13 (DIN 1.2344) Hot Worked Steel, but shoulder's material was made of AA7075 Aluminum Alloy due to its high thermal conductivity. A thrust bearing separated the pin from the shoulder and its main purpose was to hold the shoulder stationary relative to pin. Pin diameter was 10 mm and threaded with standard pitch. The shoulder's width and length were 28 and 250 mm, respectively. The shoulder's surface was coated with PTFE (Teflon). The picture of tooling system with designed fixture is demonstrated in Figure 2. As it can be seen in this figure, a NC milling machine was utilized for FSW of HDPE sheets. The designed fixture is made of cast iron. However, a thin sheet made of 316 L stainless steel was located under HDPE sheets to play the role of backing plate. Low thermal

Table 1. The properties of HDPE material.

Density (g/cm³)	Tensile strength (MPa)	Elongation at break (%)	Flexural strength (MPa)	Melting point (°C)
0.94	18	>300	28	120 - 130

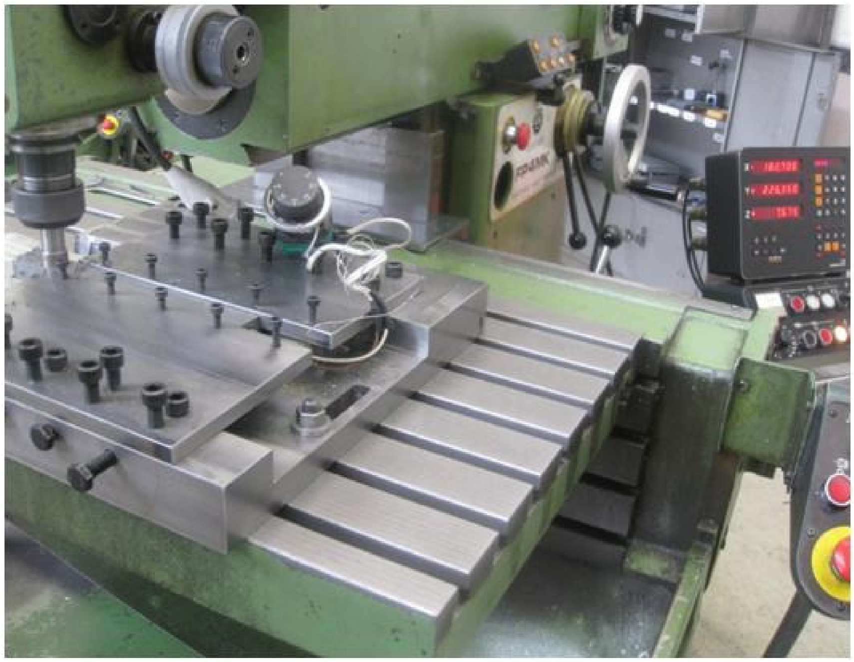

Figure 2. Heat assisted friction stir welding of HDPE sheets.

conductivity of stainless steel is a major reason to select this material.

The process parameters investigated under multiple levels. Pin rotational speeds were 1000, 1250 and 1600 rpm. Shoulder temperatures of 80, 110 and 140°C were examined. Welding speeds had values of 10, 25 and 40 mm/min. To make a judgment about the effects of welding parameters on mechanical properties of the welded plates, every parameter was investigated separately, while the others were kept fixed. Selected conditions, in which the effects of welding parameters were studied, are given in Table 2. To ensure that shoulder applies enough pressure on work pieces, a tool-offset depth is required during plunge step of the process. Optimum value of 0.5 mm was achieved for plunge depth through experimental tests. It has been observed that in high quality welds, dwell step require at least 10 to 15 s. In other words, when full depth with predefined offset was achieved, the tool was allowed to heat the material in order to create a pool of semi-molten polymer. At the end of the welding process, all welds were allowed to cool for 10 min, while still clamped in the fixture. This would reduce probability of distortion after a heating cycle that occurs during welding.

Tensile tests were performed by Zwick/Roll (model TIFR010THA50) device with autograph capability and samples were extracted from each welded part in accordance with ASTM D638 standard. Three specimens were obtained for evaluating properties of each welded sample. Three point bent test was done according to ASTM D790 standard with GT-7010A2 device manufactured by Gotech Company. For making judgment about welding effects on microstructure of polyethylene plates in various conditions, a photolastic Inc.67 Lincoln polarscope and a LEICA DMRX polarized microscope were utilized. For microscopic evaluations, welded samples were cut through a LEICA RM2135 microtome device in 10 µm thickness.

RESULTS AND DISCUSSION

Mechanical properties

Average ultimate tensile and flexural strength of samples are given in Table 3 and diagrams of data are shown in Figure 3. In all processing conditions, the plunge depth was same and 0.5 mm. In other words, designed tool is operated with about 0.5 mm of the tool on contact with the workpiece; any additional workpiece contact will produce significant amount of flash around the shoe. As the penetration depth of tool shoulder increases, more pressure applied to the material exists at the surface of the sheets. Since these surface materials are completely melted, increasing pressure will results in outpouring of them from weld nugget, consequently leads to thickness reduction. Therefore, tensile and flexural strength decrease due to stress concentration in this area. If the penetration depth is selected lower than 0.5 mm, the

Table 2. Welding parameters selected in the present study.

Test number		Rotational speed (rpm)	Welding speed (mm/min)	Heater temperature (°C)
0	without coating	1000	25	110
1	Shoulder coated	1600	25	80
2	Shoulder coated	1600	25	110
3	Shoulder coated	1600	25	140
4	Shoulder coated	1250	25	110
5	Shoulder coated	1000	25	110
6	Shoulder coated	1250	10	110
7	Shoulder coated	1250	40	110

Table 3. Data obtained from tensile and three points bend tests.

Test number	Tensile strength (MPa)	Flexural strength (MPa)
0	15.5	21
1	16	23.5
2	16.5	22
3	17.5	24.5
4	17	23
5	15	20
6	15.5	25
7	13	21

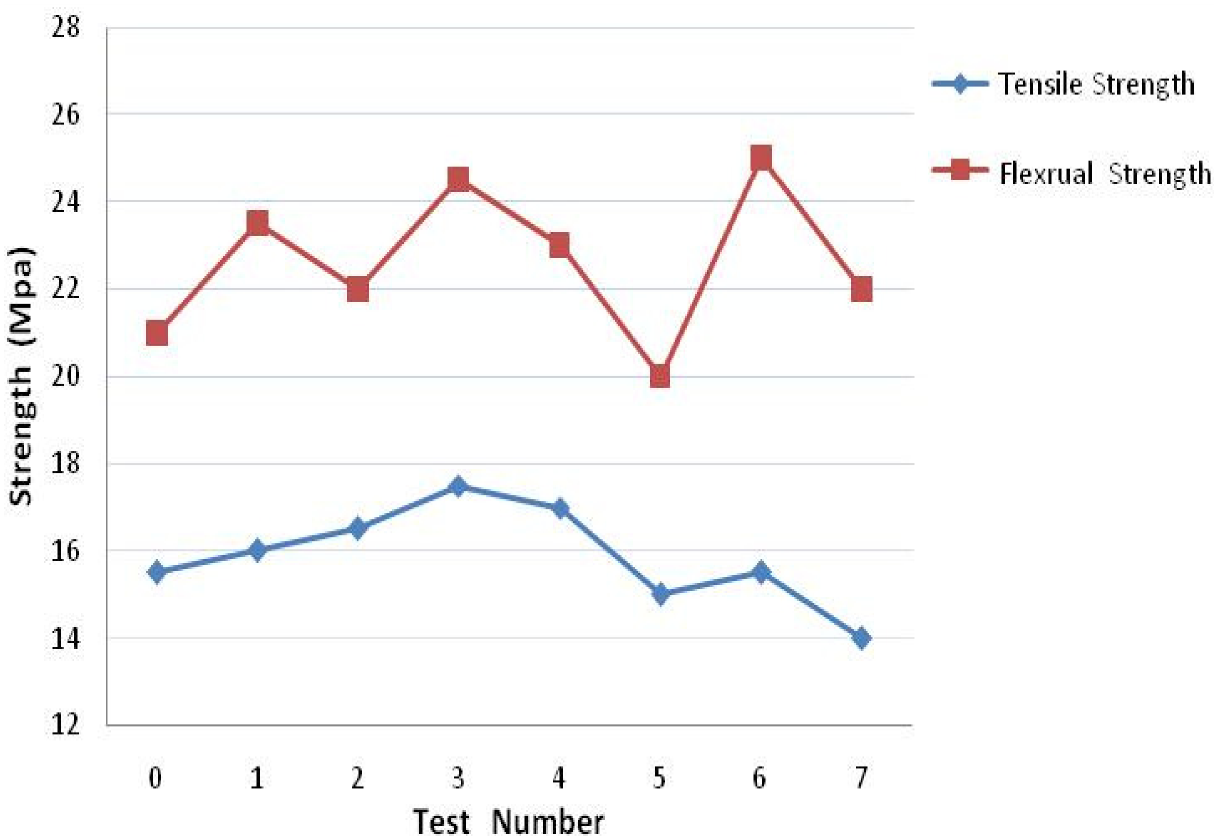

Figure 3. Diagram of tensile and flexural strength of welded samples.

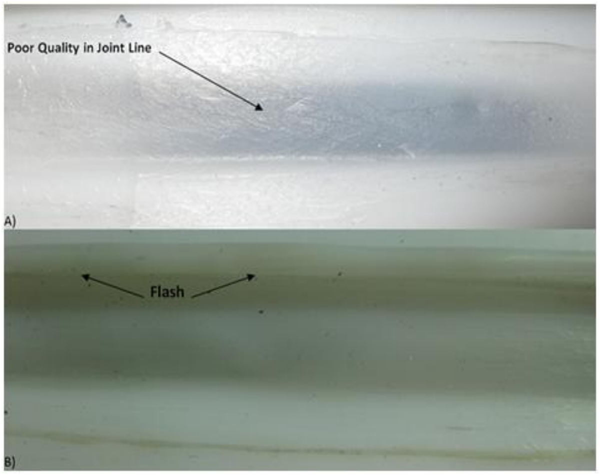

Figure 4. Effect of tool plunge depth on joint surface quality: (a) lower plunge depth and (b) higher plunge depth.

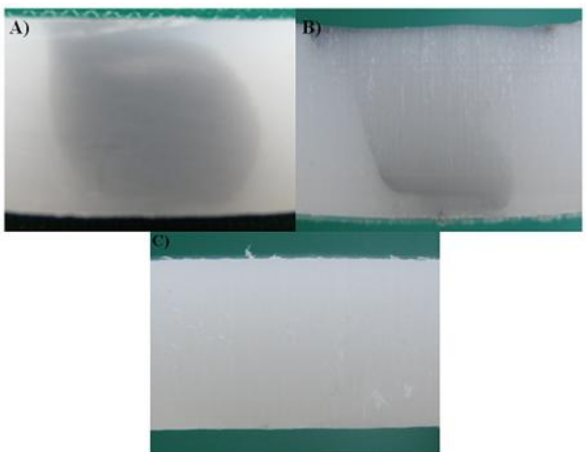

Figure 5. Macroscopic sections that illustrated material degradation in various shoulder temperature: (a) the material at stir zone is degraded in test 1, (b) material degradation occurred only in bottom of welding zone in test 2 and (c) a sound weld without any degradation in test 3.

shoulder will ride on a cushion of material that will smear across the joint line, which in turn lead to low quality joints. This phenomenon is demonstrated in Figure 4.

It is worth noting that a dwell time is necessary to start the process. Contact of the pin with the workpiece creates frictional heating and softens the workpiece material; contacting the shoe shaped shoulder to the workpiece increases the workpiece heating, expands the zone of softened material. In general, this step is necessary to heat the material in order to create a pool of semi-molten polymer. If the welding process starts without this step, the bonding between molecules of two-welded part will be so weak, since they will not reach melt temperature. However, if the tool dwells (or undergoes only rotational motion in one place) more than 15 s, degradation of polymeric chains will occur in stir zone due to excessive heating action of pin.

In the first step of this work, the temperature of shoulder is investigated. It is important to note that measurement of the temperature during this process is carried out through embedded thermocouple, which is located inside the tool shoulder. When the temperature of shoulder surface raise up, this thermo-controller will switch off the heater and control the temperature. In addition, when additional heat is needed, the heater will switch on. By comparing examination numbers of 1, 2 and 3, it can be seen that in the same conditions (rotational speed of 1600 rpm and welding speed of 20 mm/min) with an increase in heater temperature, ultimate tensile and flexural strength raise up to base material strength. From microstructure observations, it can be concluded that material degradation in joint line is responsible for such a change (Figure 5). In metals, friction stir welding is a solid-state joining method, whereas FSW of polymers is not strictly a solid-state process (Strand, 2004). This can be attributed to inherent properties of a polymeric material, because it consists of molecules of different lengths, and consequently different molecular weights, so the material do not have single melting point, but melting range. Thus, during this process bits of solid material are suspended in enough molten material. At high rotational speeds, when the shoulder temperature was 80℃ (test 1), polyethylene did not reach to its softening temperature. Consequently, there was not enough molten material, and due to low thermal conductivity of polymeric materials, which result in high thermal concentration, weld nugget degradation of polymer occurred because pin stirring action increase the temperature. Therefore, in low shoulder temperatures, the joint efficiency was low. By rising temperature to 110℃, a reduction in the amount of degraded materials has been observed at the joint line; thereby, the tensile strength goes up to 16.5 (MPa). When the heater temperature is set to 140℃, the problem of material degradation was eliminated and in respect of tensile strength, performance of joint is similar to that of base material. Moreover, ultimate flexural strength reached its highest amount. This may be contributed to the size of weld root defect, which will be discussed in the micro-scopic observation part.

In the second step of the present study, the rotational speed of tool was investigated, because it was found that this parameter is very critical and FSW of polymers is very sensitive to it (Rezgui et al., 2010; Strand, 2004). When friction stir welding is applied to joining metals, tool rotational speed is a major factor that significantly affects the amount of heat produced through stick or slide mechanism. In addition, rotating speed of pin in heat assisted friction stir welding of polymeric materials has

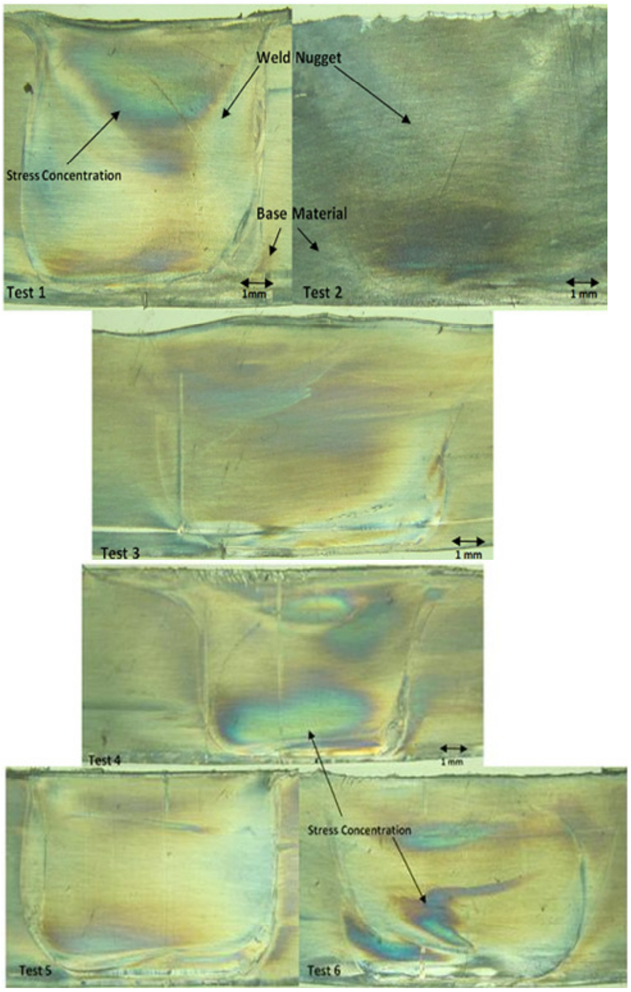

Figure 6. Microstructure observations of weld sections obtained from photolastic polarscope device.

considerable effect on local temperature and the amount of residual stresses produced during welding process. By comparing tests number 2, 4 and 5, it can be seen that higher rotational speeds is the reason for higher joint performance. With increasing rotational speed of pin, the local temperature of material goes up. This is due to low thermal conductivity of polymeric material, which leads to heat concentration in weld nugget. As a result, in the same shoulder temperature in welds which were created at high rotational speeds, more molecular chains reached to melting temperature and consequently more molten material would be presented around the pin that results in an improved stirring condition and weld performance. It may contribute to easily move and form the mixture in these welding conditions. This was in great compatibility with results of other studies that utilized conventional FSW method for joining plastics (Strand, 2003; Bozkurt, 2011). In these works, it was stated that welds with high performance are achieved in high rotational speeds. It is necessary to note that as mentioned earlier, in higher rotational speeds, the shoulder temperature should be high enough that avoids material degradation. In other words, increasing the tool rotational speed without increasing shoulder temperature would results in material degradation and thereby low mechanical strength.

Another important parameter that affects the mechanical properties of friction stir welded joint is transverse speed (or welding speed) of the tool. From Table 3, it can be seen that in transverse speeds of 10 and 40 mm/min, the ultimate tensile strength is lower than 90% of base material strength. In friction stir welding, tool transverse speed is strongly determining the cooling rate of joint material. In higher amount of transverse speeds, the materials in joint line would not have enough time to cool and will contract and pulled away, However, In lower amount, the tool stirring action will lead to tearing of joint materials. In both cases, the joint efficiency will decrease significantly. Therefore, it is concluded that 25 mm/min is the best transverse speed for heat assisted friction stir welding of polyethylene sheets.

Microstructure

Microstructure observations that were obtained from photolastic polarscope device are as shown in Figure 6. This device utilizes polarized light in which each parts of the weld section appeared in different colors, because process left different effects on various regions of it. In tests number 1 and 5, the stir zone is limited to pin area due to low shoe temperature and rotational speed, respectively. In these test conditions less heat production through weld line and consequently narrow weld nugget is responsible for reduction in tensile and flexural strength. As melting action of tool is confined to pin area, there would not be sufficient connection between molecular chains of weld nugget and base material. However, in test conditions, such as those that exist in tests number 3 and 6, welding parameters caused adequate heat production and the weld nugget extended to base material that results in remarkable improvement of joint performance. In accordance with what was discussed in previously, from mechanical point of view, the optimum test conditions are those of test number 3 and weld performance is very similar to not-welded polyethylene sheet. However, one noticeable point is that when polymeric materials joined by friction stir welding, a substantial drop has occurred in elongation of tensile test samples, due to heating cycle experienced by material. So far, any reasonable answer has not been found to "how this mechanism affects the ductility of base material". It may be attributed to low crystalline amount and stress concentration in weld nugget zone. The stress concentration areas in weld nugget are demonstrated in Figure 6.

One of common imperfections encountered in friction

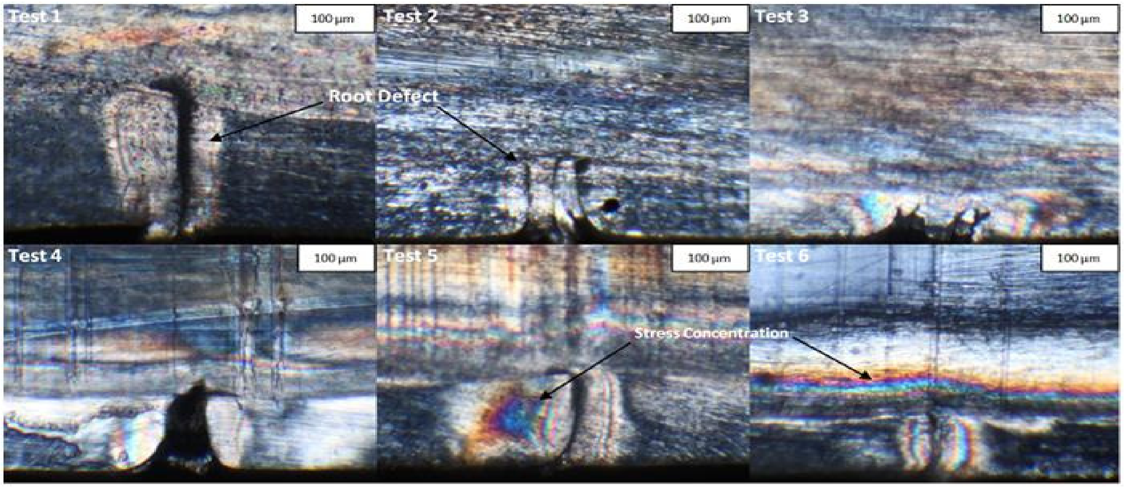

Figure 7. Root penetration defect of various test condition.

Figure 8. Effect of tool shoulder coating on surface quality of welded polyethylene sheets: (a) welding by shoulder without coating and (b) welding by coated shoulder.

stir welding is root flaws or incomplete root penetration. Although, there are several causes for incomplete root penetration (Mishra and Mahoney, 2007), the major reason is attributed to tool design, because there is always a gap between bottom of pin and anvil. In view of mechanical properties, this imperfection has substantial influence on tensile and flexural strength. When welding parameters were selected in order that tool could produce sufficient heat to melt whole weld nugget, it resulted in reduction of this imperfection area. Figure 7 shows root penetration defect in various test conditions. From this figure, it can be inferred that optimum test conditions have the same conditions of tests number 3 and 6, which produced heat and consequently the amount of molten material inside weld nugget, is maximum. The size of root penetration defect has a strong relationship with flexural strength. The bending sample was tested in root down configuration. Therefore, when the root is not welded properly, a stress concentration develops immediately as a stress is applied to the joint. Thus, in welded samples with small size of root defect, resistant of welded part to tensile forces is increased. Experimental investigations show that the forced contact between tool shoe and polyethylene sheets poses a problem. When the molten film of polymeric material is being developed, the material tends to stick to the shoulder of the tool. This problem results in residual stress concentration on the crown of weld, thereby leading to considerable reduction of mechanical strength because in tensile and flexural tests, this region is very susceptible to crack propagation. This problem can be prevented by coating the tool shoulder (shoe) with PTFE. Furthermore, the coating of tool affects the surface quality of welded samples. Figure 8 indicates that shoulder coating could significantly affect the surface quality by avoiding sticking molten material to tool shoe.

Conclusions

By utilizing heat assisted friction stir welding, polyethylene sheets could be joined with ultimate tensile strength of higher than 95% of base material strength. However, in some samples, weld efficiency is equivalent to base material, which cannot be achieved by similar conventional methods. Considering the aforementioned discussion, the following conclusions can be drawn about the effect of process parameters on mechanical properties and microstructure of heat-assisted friction stir welded polyethylene sheets.

In general, higher rotational speed resulted in higher tensile and flexural strength, with increasing rotational speed of pin, the local temperature of material would rise up. This can be attributed to low thermal conductivity of polymeric material, which leads to heat concentration in weld nugget. As a result, more molten material would be presented in joint line that leads to improved stirring conditions as well as weld performance. It should be noted that high rotating speed in combination with low shoe temperature result in material degradation, so by increasing temperature of the shoulder, ultimate tensile and flexural strength of joint rose up due to less degradation in joint line. Higher rotational speeds and shoulder temperature caused extending weld nugget to base material, which results in good combination of molecular chains as well as reduction of incomplete root penetration, as a result, higher weld performance was achieved. From mechanical tests results and microscopic observations, it can be concluded that the optimum value of transverse speed for heat assisted friction stir welding of polyethylene sheets is 25 mm/min. Shoulder coating improves residual stress concentration on weld crown caused by sticking molten material to tool and consequently, it can result in higher joint performance. Moreover, it has been shown that samples joined with coated tool have very good surface quality.

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