Effects of double passes of the tool on friction stir welding of polyethylene

ARMAĞAN ARICI*, TAMER SINMAZ
Department of Mechanical Engineering, Kocaeli University, 41040 Izmit, Kocaeli, Turkey
E-mail: ariciarmagan@hotmail.com

The need to produce larger, more complex parts from polymers has created an increased need for joining, particularly thermoplastics [1]. Injection moulding has led to increased use for disposable products because the plastic parts can be made inexpensively and in high volume. However, injection moulding is not capable of producing all type of structures and the most cost-effective way to make them will often involve moulding two or more parts and joining them together.

Mechanical fasteners, adhesives, and welding processes can all be employed to form joints between engineering plastics [1]. Adhesives can provide good properties and fully sound joints, but they are difficult to handle and slow to cure. Also joint preparation and surface cleanliness need to be given importance in adhesive bonding. Mechanical fasteners can join two components quickly, but they do not provide a leak tight joint, and the localized stresses may cause them to pull free of the polymeric material.

Welding can be used to produce bonded joints with mechanical properties that approach those of parent material. Plastic welding processes can be divided into two groups (1) processes involving mechanical movement to produce heating (ultrasonic welding, friction welding, vibration welding) (2) processes involving external heating (hot plate welding, hot gas welding and resistive and implant welding) [2]. Welding processes for joining plastics involve three steps: (a) heating the welding surfaces to a viscous or a molten state (b) bond formation by application of pressure (c) holding the pressure until hardening.

Friction stir welding (FSW) is a new solid state welding process, which is developed and patented by The Welding Institute (TWI-Cambridge, UK) in 1991 [3, 4]. In this process, a rotating cylindrical shouldered tool with a pin is driven into the butted plates [5]. The pin used at weld is typically slightly shorter than the thickness of the weld plates and its diameter is approximately equal to the thickness of the weld plates [6]. The shoulder may be three times the diameter of the pin. The heat, which is originally derived from the friction between the welding tool (including the shoulder and the pin) and the welded material, causes the welded material to soften at a temperature less than its melting point. The softened material underneath the shoulder is further subjected to extrusion by the translation of the rotational tool along the joint line between the welded plates. So, the three welding steps of the conventional processes are applied at one step.

The primary research about FSW has been focused on aluminum alloys. By this welding process many advantages appeared as follows: the elimination of the welding defects named crack and porosity often associated with fusion welding processes, reduced distortion, joint edge preparation not needed, can be carried out in all positions, can join conventionally non-fusion weldable alloys and improved mechanical properties of weldable alloys [4–8].

In recent years researchers have been trying to adapt FSW technology to the joining of thermoplastic materials. TWI research group studied FSW by rotating tool, but because of the formation of voids along the length of the weld they focussed on FSW of polymers using a vertical reciprocating blade. They have managed to produce welds in 6 mm PVC sheet [9]. The Brigham Young University in the United States has investigated this process and has a patent for FSW in combination with a heated shoe, which is claimed to eliminate voids and improve mixing. Several polymeric materials have been successfully welded included polyethylenes (LDPE, HDPE, UHMWPE), polypropylene, nylon, polycarbonate and ABS [10].

In literature there is no published study about the microstructure of FSW of polymers. But there are some studies investigating the effects of processing parameters on microstructure. As reported in [10] the microstructure of welded zone is divided into four different regions: 1—central region, 2—advancing interface, 3—retreating interface, 4—bottom disturbance region. They welded PP sheets with a single pass of the tool. It created root defect, which is defined as an area at the bottom of the joint that is not welded. The bottom of each joint was not stirred, and thus left unwelded. This defect is the weakest region of the welded zone. Root defect is responsible for all tensile and bending failure. At this point we aim to apply FSW by using double passes of the tool. In first pass we welded approximately half of the material, then we turned back and clamped the sample for the second pass of the tool. After second pass of the tool, no root defect appeared.

The aim of this study was to demonstrate the joining of polyethylene plates by FSW using a rotating cylindrical shouldered tool. We investigated the optimum parameters of FSW. The mechanical performance of

*Author to whom all correspondence should be addressed.

0022–2461

the welded polyethylene (PE) was investigated by tensile and bending tests. Also, the fracture locations of the welds were observed.

Medium density polyethylene (MDPE) with the 3 and 5 mm thick plates was used. The plates were cut into rectangular welding samples of 200 mm long by 80 mm wide. The samples were placed on a flat metal plate and clamped with a vice to avoid separation during the FSW process. Then, the samples were longitudinally butt-welded by using rotating cylindrical shouldered tools. The shoulder diameter was 16 mm, the pin diameter was 5 mm and the pin length was 2.8 mm.

The tensile and bending tests were performed according to EN ISO 527 and ISO 178, respectively. The tensile and bending tests were carried out using an Instron 4411 test machine at a crosshead speed of 100 and 50 mm/min, respectively. The span of 80 mm was used in bending tests. The fracture locations were observed using an optical microscope.

MDPE samples with 3 mm thickness were welded by a single pass of the tool. The performances of different rotation speeds (600, 800 and 1000 rpm), welding speeds (12.5, 25, 40 and 60 mm/min) and tool angles (0° and 1°) were investigated. We observed that there was a root defect lay out along the joint line at the bottom of the samples. The thickness of this root defect was approximately equal to the difference between the sample thickness and the pin length ($\approx$0.2 mm). As a result of unwelded area at this region, the joints were easily separated in two parts by bending with a small force even by hand.

To eliminate the root defect, the welds were carried out using double passes of the tool for 5 mm thick PE samples. We observed that the rotation speeds of 600 and 800 rpm were not high enough to produce necessary heat to soften the material. On the other hand 1000 rpm is found as appropriate rotation speed of the tool which softened the material to produce suitable welded joints.

Because of the reason explained above, we used the rotation speed of the tool as 1000 rpm for 5 mm thickness samples. The performances of different welding speeds of 12.5, 25 and 40 mm/min and tool angles of 0° and 1° were investigated.

Table I shows the tensile properties of FSW joints of 5 mm thickness samples. We observed that welded samples were fractured without showing a yield necking. Table I provides the results of tensile strength of welded samples and types of fracture locations. It should be noted that the plastic materials can be used until their yield point. The yield point should be evaluated as a design criteria because at the yield point there will be a plastic deformation. So the tensile strength of the welded parts corresponds to the yield point of original specimens. The tensile yield strength of original PE specimen was 20 MPa.

The results indicated that the specimens welded with a tool angle of 1° were better than the tool angle of 0°. We observed that the 1° tool angle kept the softened materials remain in the welded zone. This resulted in a better weld surface. No void or crack formation was observed in the weld zone. The tensile strength results of FSW joints were approximately the same with the tensile yield strength of original specimen. The lowest tensile strength value of 15, 81 was 79% of the original PE specimen.

The weld region after the FSW process is seen in Fig. 1. The examination of the fracture locations of the weld joints clarifies the weakest part of the joint. It is observed from the fracture surfaces of tensile test specimens that there are five different fracture locations in the joint region. The schematic illustrations and the photographs of these locations are seen in Fig. 2. Also, the types of fracture locations were provided in Table I. There was a close relationship between the tensile test results and fracture locations. The fracture out of the welded zone gave higher strength.

The bending test results were provided in Table II. We performed two types of bending tests. In the first type, the first pass weld zone was subjected to tensile stress and in second type, the second pass weld zone was subjected to tensile stress. In Table II it is possible to get the results of bending as crack existence regarding to bending type, failure displacement, bending angle (up to crack formation) and yield displacement.

Crack formation after bending was occurred as in type d (Fig. 2). Bending test results showed that a tool angle of 1° gave better bending properties similar to tensile test results. A crack formation occurred in A, B, C and D coded specimens. There was a remarkable tendency to crack formation in type 2 bending test. There was no crack formation in samples, which are coded by E and F.

By using double passes of the tool on FSW of polyethylene, we eliminated the root defect, which has an important role on failure initiation in the welding zone. We got satisfactory tensile and bending

TABLE I The results of tensile tests

Sample code	Tool angle (°)	Welding speed (mm/min)	Tensile strength (MPa)	Types of fracture location
A	0	12.5	16.46	Type c
B	0	25	19.35	Type b and type e
C	0	40	15.81	Type a
D	1	12.5	20.45	Type e
E	1	25	19.30	Type b and type d
F	1	40	17.70	Type b and type d

TABLE II The results of bending tests

Sample code	Bending type	Crack formation	Failur displacement (mm)	Yield displacement (mm)	Bending angle (°)
A	Type 1	Yes	11.60	11.51	18.4
A	Type 2	Yes	15	12.71	23.2
B	Type 1	No	–	19.77	–
B	Type 2	Yes	30	18.01	40.6
C	Type 1	No	–	17.10	–
C	Type 2	Yes	32	17.71	42.4
D	Type 1	Yes	14.4	14.33	22.3
D	Type 2	Yes	18	16.57	27.2
E	Type 1	No	–	17.69	–
E	Type 2	No	–	16.92	–
F	Type 1	No	–	16.86	–
F	Type 2	No	–	18.02	–

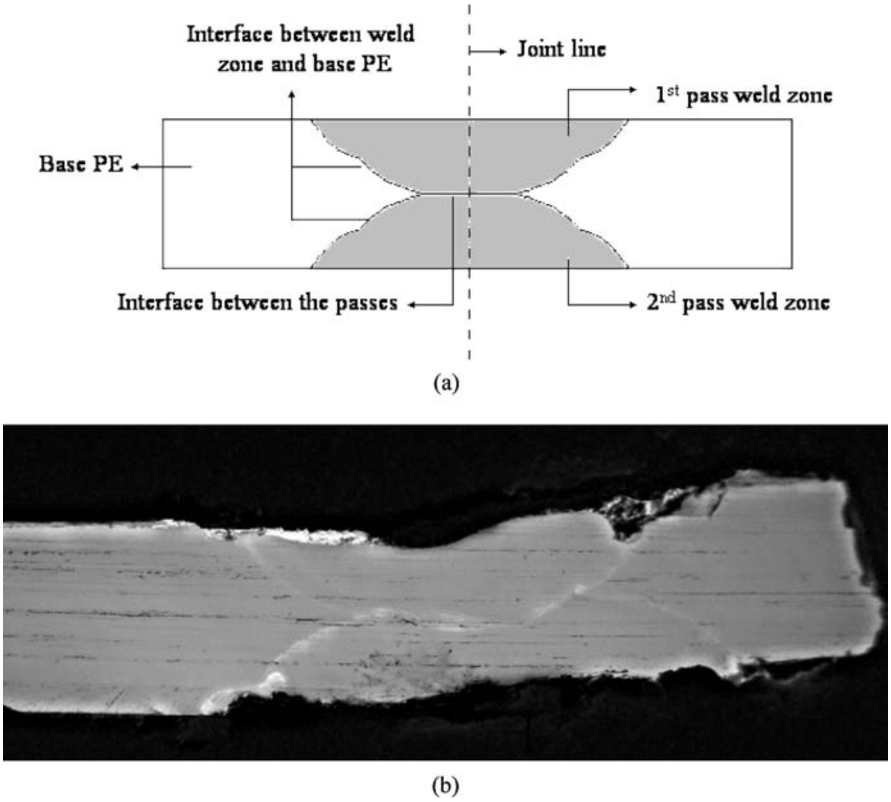

Figure 1 The welded zone for double passes FSW (a: schematic illustration, b: photograph).

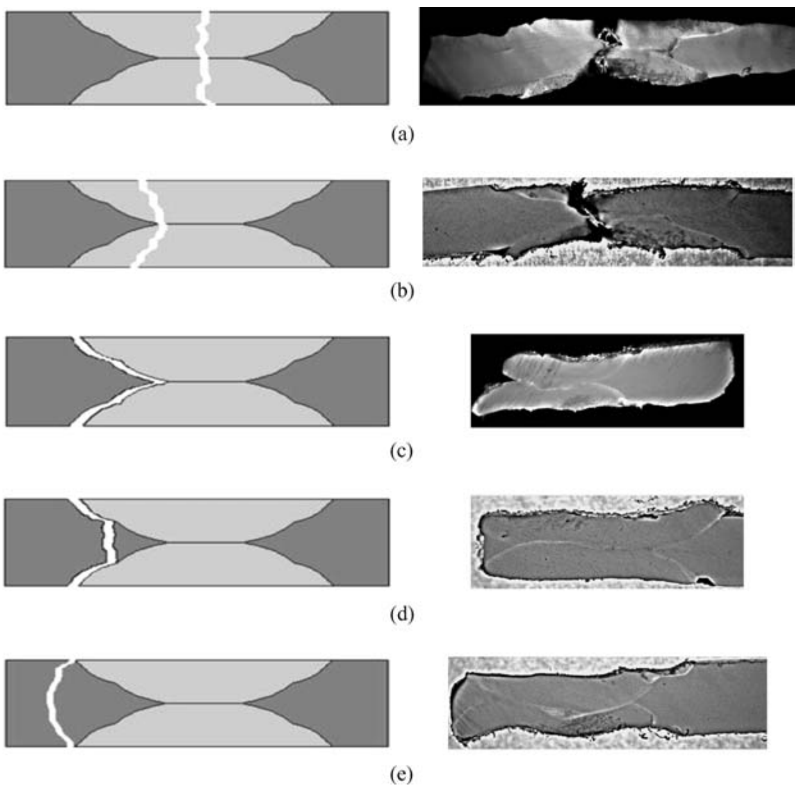

Figure 2 The types of fracture locations.

results. The tool angle of 1° and the welding speed of 25 mm/min was found as optimum parameters in FSW of PE for 5 mm thick plates.

Acknowledgments
The authors would like to thank Mr Abdulkadir Yayla for the production of the welds.

References

1. http://www.ewi.org/technologies/plastics/intro.asp
2. R.W. MESSLER Jr., "Joining of Advanced Materials" (Butterworth-Heinemann, USA, 1993).
3. W. M. THOMES, E. D. NICHOLAS, J. C. NEED HAM, M. G. MURCH, P. TEMPLESMITH and C. J. DAWES, Friction Stir Butt Welding, International Patent Application No. PCT/GB92/02203 and GB Patent Application No. 9125978.8 (6 December 1991).

4. M. BOZ and A. KURT, *Mater. Design* **25** (2004) 343.
5. C.M. CHEN and R. KOVACEVIC, *Machine Tools Manufacture* **43** (2003) 1319.
6. M. GUERRA, C. SCHIMIDT, J. C. Mc CLUERA, L.E. MURR and A. C. NUNES, *Mater. Characterization* **49** (2003) 95.
7. M. PEEL, A. STEUWER, M. PREUSS and P. J. WITHERS, *Acta Materialia* **51** (2003) 4791.
8. H. J. LIU, H. FUJI, M. MAEDA and K. NOGI, *J. Mater. Process. Technol.* **142** (2003) 692.
9. ASM International. Reciprocating Friction Stir Welding Joins Thermoplastics, Advanced Materials & Process 158 (September 27).
10. R. STRAND SETH, Effects of Stir Welding on Polymer Microstructure, MSc Thesis, Department of Mechanical Engineering, Brigham Young University (April 2004).

Received 3 September
and accepted 28 October 2004