Mechanical behavior of friction stir welded high-density polyethylene sheets

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Abstract

In the present work, sheets of high-density polyethylene, reinforced with strips of polypropylene using a friction stir welding technique were executed. Welding was carried out using a friction stir welding tool of 20 mm shoulder diameter and 5 mm for both pin diameter and pin length with zero tilt angle, the percentages of polypropylene added to the welding zone were 15, 20, 25, 30% (as a percentage of the added polypropylene to the welding zone), the recommended high tool rotation speed and low tool travel speed (520 rpm, 20 mm/min, respectively) were applied in all tests, the plunge depth was 0.5 mm (the penetration depth of tool shoulder from workpiece surface), dwell time at the event of submerging the pin into the faying surfaces and before initiating the tool travel speed was 45 seconds. Mechanical tests, represented by flexural and impact tests, exhibited an improvement in the mechanical properties of the welded specimens for the case of 25% added polypropylene. Friction stir welding has extraordinary potential to create imperfection-free joints and to initiate a high-quality weldment of high-density polyethylene sheets reinforced by polypropylene strips.

1. Introduction

Friction stir welding (FSW) is a relatively new solid-state joining process [1]. It was invented at The Welding Institute (TWI) in the UK in 1991 [2], [3] and was initially applied to aluminum alloys [3], [4]. FSW has the capability of fabricating steel joints with excellent toughness and strength, and to perform high-efficiency weldments as compared with fusion welding [5]. Other similar and dissimilar materials welded by FSW include but are not limited to magnesium alloys, copper alloys, titanium alloys [6] and zirconium alloys [7]. Welding is carried out by a non-consumable rotating tool consisting of two parts, a shoulder and a pin (probe). The tool rotates at its axis, touches the workpiece surface, creates downward pressure, generates heat through the friction between the tool and the workpiece and causes plastic deformation in a relatively thin layer below the bottom surface of the shoulder, and moves longitudinally at the two workpieces’ interface. The rotating pin mixes the adjacent plasticized material.
in the stir zone and creates a joint without fusion [8]. This joint is created due to the thermomechanical treatment of the interface surface. Thermoplastic materials have broad applications in modern industry as a result of their lightweight properties, advantages in better productivity, corrosion resistance, electrical properties, flexibility in design and manufacturing, etc. However, large scale and complex shape components made of polymers are often required to be produced by joining technologies [9], [10]. The engineering thermoplastics have been considered by the leading manufacturing industries in recent times. Their lightweight property, which enhances the overall efficiency, is a significant reason for their popularity [11]. Methods for the welding of thermoplastics can be sorted into three main categories: chemical joining techniques, mechanical joining techniques, and thermal joining techniques [12]. The demand for rapid, reliable, and high productivity welding methods for plastic has increased due to the low productivity of fusion welding, which requires a long time to perform the welding procedure. The use of FSW to join plastics is the optimum solution and new means by which to expedite the welding process, increase productivity, and to reduce manufacturing cost.

Attempts to join thermoplastics by FSW started in 1997. In 1999, various types of FSW tool had been designed by Clark for the joining of thermoplastic materials, and actual studies on FSW of thermoplastic began to emerge. Comprehensive study began in 2005 and the FSW was applied to many plastic materials including polymer composites, polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), etc. [10]. These can be joined with similar, as well as dissimilar, polymer composites (subject to certain conditions, such as glass transition temperature, rheological properties etc.) [13].

Ehsan & Amir [14] investigated the effects of friction stir welding parameters on the flexural strength of high-density polyethylene (HDPE) sheets using the RSM method. They found that welding at a high tool rotation speed (TRS) and a low tool travel speed (TTS) increased weld flexural strength by reducing the size of defects. The optimum welding parameters to achieve optimum flexural strength were 1400 rpm & 25 mm/min. The flexural strength of the welded sample was about 96% of base material strength.

M. Zemri & A. Brahami [15], studied the process of friction stir welding of polyethylene plates and optimized the parameters to produce a weldment of a good surface quality and a good weld joint. They used tensile tests to estimate the optimum welding conditions and concluded that the optimum mechanical properties can be achieved when applying a TRS of 1000 rpm and TTS of 80 mm/min. J Oleiwi et al. [16], studied the mechanical properties of HDPE plates by blending different percentages of polyvinyl chloride (PVC), PP and styrene acrylonitrile (SAN) to the base metal HDPE, using the friction stir processing technique. The optimum mechanical properties for the values of tensile strength and hardness were maintained when adding 15% ratio of PVC to the welding zone.

M. Moreno et al. [17], studied the effects of process parameters on the tensile strength and hardness, and crystallinity in HDPE welded joints using FSW and a non-rotational shoulder tool were established. An operational window process was from 1036 to 846 rpm, and 14 to 25 mm/min of TRS and TTS, respectively, producing welded joints free of discontinuities and overheating in the stir region. Hardness distribution across welded joint was more strongly affected by TRS; however, the effect of the TTS on this behavior was weaker.

The quality of FSW is based on many factors, including the welding parameters represented by TRS and TTS along the line of the joint. The stirring and mixing of material around the pin are due to the rotation of the tool, and the longitudinal movement of the tool transfers the stirred material from the front to the back of the pin and finishes the welding process. Tool geometry and joint design have a remarkable impact on the material flow pattern and temperature distribution, thereby affecting the microstructural evolution of the material [1].
The objective of this research is to establish sound and defect-free weldments and to optimize the flexural properties of the friction stir welded joints of HDPE sheets, based on the addition of a percentage of PP to the welding zone.

2. Experimental procedure

2.1. Materials and methods

In the present work, sheets of HDPE with thickness of 6 mm were supplied and machined to the final dimensions (200x100 mm) on a conventional vertical milling machine. The PP strips were also machined to 200 mm length and 6 mm thickness, with a variable width (2.25, 3, 3.75, and 4.5 mm) where the additive percentage in the welding zone was supposed to be 15, 20, 25, and 30 %, respectively. The set of the specimens is shown in Figure 1.

The FSW tool used in this work was shoe tool type, made of H13 tool steel, the shoulder diameter was 20 mm, and the pin length and diameter were 5 mm, the shoulder was mounted on a thrust bearing and the assembled tool was set on aluminum plate as shown in Figure 2. The sheets of HDPE with a strip of PP were mounted on a vertical milling machine (model Knuth, made in China) using a fixture composed of two pieces made of steel and 20 mm thick-backing plate made of high carbon steel. The designed fixture prevented movement of the specimens during welding and guided the shoe tool. The TRS and TTS were (520 RPM, 20 mm/min) respectively, in all process conditions, the plunge depth was 0.5 mm (the penetration depth of tool shoulder from workpiece surface).

In the first step of FSW, dwell time was 45 seconds (the time when the pin penetrated the workpiece, and shoulder face touched the specimen and before the initiation of the TTS to allow generation of required heat and create a pool of semi-molten polymer), and then the tool moved along the welding line. When the tool reached the final position at the end of the welding process, the shoe tool remained in its location for 12-15 minutes to allow cooling of the welded specimen and to prevent any distortion after the welding procedure.

2.2. Test procedure

Flexural and impact tests were conducted for five welded specimens, based on the percentage of PP which was 0, 15, 20, 25, and 30% for each specimen. The 3-point flexure test is recommended for
polymers. The test specimens were prepared according to ASTM D790 standard [18], machined on a vertical milling machine to the final standard dimensions (100x10X5 mm), these specimens were cut perpendicular to the welding direction. Six specimens for each weld were cut and tested, three specimens were tested from the face of the weld while the remaining three specimens were tested from the root of the weld, and the average readings were considered. Flexural strength, flexural modulus and maximum shear stress were obtained by using a universal testing machine (model WDW 200 E, made in China), the crosshead speed was 5 mm/min, and the tests were executed at room temperature.

Impact testing is recommended to measure impact resistance, which is one of the most essential properties of a component. It is a critical measure of service life, and it involves the perplexing problem of product safety and liability; therefore, the test was done to evaluate the quality of the welded specimens. Three specimens for each weld were cut on a vertical milling machine to the final standard dimensions (80x10x5 mm). The impact test was performed according to ISO-180 [19] by using the Izod impact test machine (model XJU-22, supplied from Time group Inc, China). Three specimens were cut from each weld, and the results obtained were a mean of three readings per experiment.

3. Results and discussion

3.1. Preliminary experiments to decide the welding parameters

A number of FSW experiments were executed to find the optimum TRS and TTS in this study, focusing on the other parameters represented by the percentage of reinforcement material. It is enough to present the selected welding parameters, that produced the best mechanical properties among several welding experiments on the sheets of HDPE without any added percentage of PP. The selected welding parameters represented by TRS and TTS (520 rpm, 20 mm/min, respectively) were applied in all tests, the plunge depth was 0.5 mm, dwell time at the event of submerging the pin into the faying surfaces and before initiating the TTS was 45 seconds.

3.2. Effect of the reinforcement material on the welding quality

The flexural test results are shown in Figures 3, 4, and 5, which show the effect of adding the PP to the parent HDPE on the flexural properties (flexural strength, flexural modulus and maximum shear stress) of the weldments. It was observed that the optimum flexural properties resulted when adding 25% of second material PP to HDPE in solitary form, and moreover, that when increasing the percentage of PP to more than 25% these properties will decrease, a phenomenon that is related to the nature of the chains of the constituent polymers, and the compatibility between the two phases of binary polymer which depends on the contributing properties of each of its components.
Figure 3. Flexural strength of (HDPE) welded sheet as a function of added (PP) polymer.

Figure 4. Flexural modulus of (HDPE) welded sheet as a function of added (PP) polymer.

Figure 5. Maximum shear stress of (HDPE) welded sheet as a function of added (PP) polymer.

The impact test results are shown in Figures 6 and 7, which reflected the same behavior as in the flexural test. Both the impact strength and the fracture toughness increased with adding PP to the sheets of HDPE and the best results were found when the percentage of PP was 25%.
Figure 6. Impact strength of (HDPE) welded sheet as a function of added (PP) polymer.

Figure 7. Fracture toughness of (HDPE) welded sheet as a function of added (PP) polymer.

As Table 1 shows, the efficiency of the FSW of HDPE with no additive of PP is 76.67% as compared to the flexural strength of the parent material. By adding a percentage of PP to the welding zone, the mechanical properties were improved, the test results show that the optimum percentage of PP that gave the best mechanical properties was 25% of PP, which increased the relative flexural strength to the value 116.66%.

Table 1. Results of flexural strength tests (mean values).

| Exp. no. | PP % | Flexural strength MPa | Relative flexural strength (%) |
|----------|------|------------------------|--------------------------------|
| 1        | 0    | 23                     | 76.67                          |
| 2        | 15   | 31                     | 103.33                         |
| 3        | 20   | 34                     | 113.33                         |
| 4        | 25   | 35                     | 116.66                         |
| 5        | 30   | 33                     | 110                            |
| Base metal | 30  | 100                    |                                 |
4. Conclusion

In this study, FSW technology conveyed an improvement in the quality of the weldments of HDPE sheets reinforced by PP strips, and these were verified by the mechanical tests represented by flexural and impact tests and compared with the mechanical properties of the weldments of unreinforced HDPE sheets. The flexural properties of all of the FSW joints that included a percentage of PP in the welding zone have been improved, as compared with the FSW of the joints of HDPE (without PP). The best flexural and impact properties were indicated in the specimen with 25% of added PP. FSW has incredible potential to create imperfection-free joints and initiated a high-quality weldment of the HDPE sheets reinforced by PP strips. Moreover, the good surface quality has been observed in the welded joints.

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