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FRICTION STIR WELDING OF POLYETHYLENE SHEETS

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ABSTRACT

Polyethylene sheets 3 mm thick were friction stir welded with a cylindrical steel pin; two pin diameters and a combination of feed rates and rotational speeds of the pin were considered for the experimentation. Moreover, a modification of the traditional friction stir welding process was investigated by adding a heating step of the pin and the samples to join. The quality of the joint was evaluated by means of tensile tests and thermal analysis. A correlation between mechanical properties and process parameters was found. Even if process optimization is required, the final performances of the joints are sufficient to assess that friction stir welding of polyethylene may be a valid alternative to conventional joining technologies.

KEYWORDS: friction stir welding, polyethylene, thermoplastics, joining.

1. INTRODUCTION

Friction stir welding (FSW) is a solid-state joining technique generally used for metal sheets. It is a patented process with a very simple basic concept. A non-consumable rotating tool with designed pin and shoulder is inserted into the edges of the plates to join. The pin traverses along the line of joint and the shoulder touches the plates. Due to friction, the tool heats the workpiece and moves the material from a side to the other. Material plastic deformation also increases the overall heat generated during the process. Localized heating softens the material around the pin and the combination of the pin rotation and translation results in producing a welded joint in solid-state [1].

Being a solid-state process, diffusion plays a central role during joining and metals are particularly suitable for this technique. Moreover, the high thermal conductivity of metals enhances material softening near the pin. Recently, some researchers have studied the application of FSW to thermoplastics but obtaining good joints is a very hard task. In fact, thermoplastic materials are poor thermal conductors and diffusion is not an efficient mechanism because of their macromolecular structure.

In 2005, Arici and Sinmaz studied the effect of double passes of the tool on FSW of polyethylene [2]. They used 5 mm thick sheets and a rotational speed of 1,000 rpm. Double passes allowed them to increase the joint mechanical properties. In 2007, Arici and Selale continued this study and found that the thickness of the welding zone decreased with increasing tool tilt angle which affects the tensile strength [3]. More recently, in 2008, Arici and Senol have also studied FSW of polypropylene sheets [4].

In the present work, the authors studied FSW of polyethylene sheets with a single pass, because double passing introduces several technical problems which affect the simplicity of FSW process. The study was performed by changing the main process parameters: pin rotational speed, feed rate, pin diameter, temperature.

2. MATERIALS AND METHODS

FSW was performed by means of a vertical-spindle column-and-knee type milling machine. A 24-kW high-speed spindle was used in a fixed position, whereas the feeding rate was provided by the machine table. A commercial 3 mm thick high density polyethylene (HDPE) sheet was used as workpiece. Samples were cut with the size of 20x30 mm^2. For each joining test, two samples were fixed in a metal frame in a butt joint configuration, in contact along the smaller edge. This frame was subsequently fixed on the machine table. Steel flat pins with a shoulder 6 mm in diameter were used for joining. In the process set-up a minimum distance about 0.2 mm was left between the pin flat surface and the bottom surface of the samples.

The pin rotational speed was changed between 3,000 and 20,000 rpm, the feed rate between 10 and 44 mm/min, the pin diameter between 1 and 3 mm.

Also the sheet and the pin temperature was changed in two different ways: by means of a hot air gun and by a heating plate. The temperature changed between the room value and 150°C.

The joint strength was measured by means of tensile tests (MTS Alliance RT/50). A distance between the grips of 30 mm was used and the testing rate was 1 mm/min. Thermal tests were also carried out with a differential scanning calorimeter (DSC, Netzsch DSC 200 PC). Some samples were extracted across the joint and DSC tests were performed from room temperature to 200°C so as to extract the melting heat.

3. RESULTS AND DISCUSSION

The evaluation of the best process conditions is a very complex tasks. Many process parameters have to be considered and their interaction is not negligible. During the first stages of the experimentation, the rotational speed and the feed rate were changed in a very wide range. The pin and material temperature was left to the room value. Figure 1 shows some joint fabricated under different process conditions. The scheme at the bottom right reports the relative motions of the pin during welding. In each joint, a hole is present at the end of the welding path and a material protrusion at the beginning. At high rotational speeds, a higher amount of heat is transferred to the material due to friction. However, if the rotational speed is excessive, the material gets parted by the pin and a poor joining is observed. In this case, the seam appears with a different structure along the two sides of the joint. On the left (i.e. where the peripheral velocity of the pin is discordant to the feed direction) it appears to be opaque. On the right (i.e. where the peripheral velocity of the pin is concordant with the feed direction) it is white. A very low force is sufficient to generate the brittle fracture of the joint. The feed rate is necessary to provide new material to the pin during the joining process. By increasing the feed rate, the material is pushed away from the seam. Moreover, the samples could move due to the feed force. For this reason, a value of 10 mm/min was chosen during the further experimentation. Good results were obtained by using a rotational speed of 5,000 rpm for the pins with 1 and 3 mm diameter. In theses cases, an uniform seam is visible with an opaque appearance, very similar to the base material.

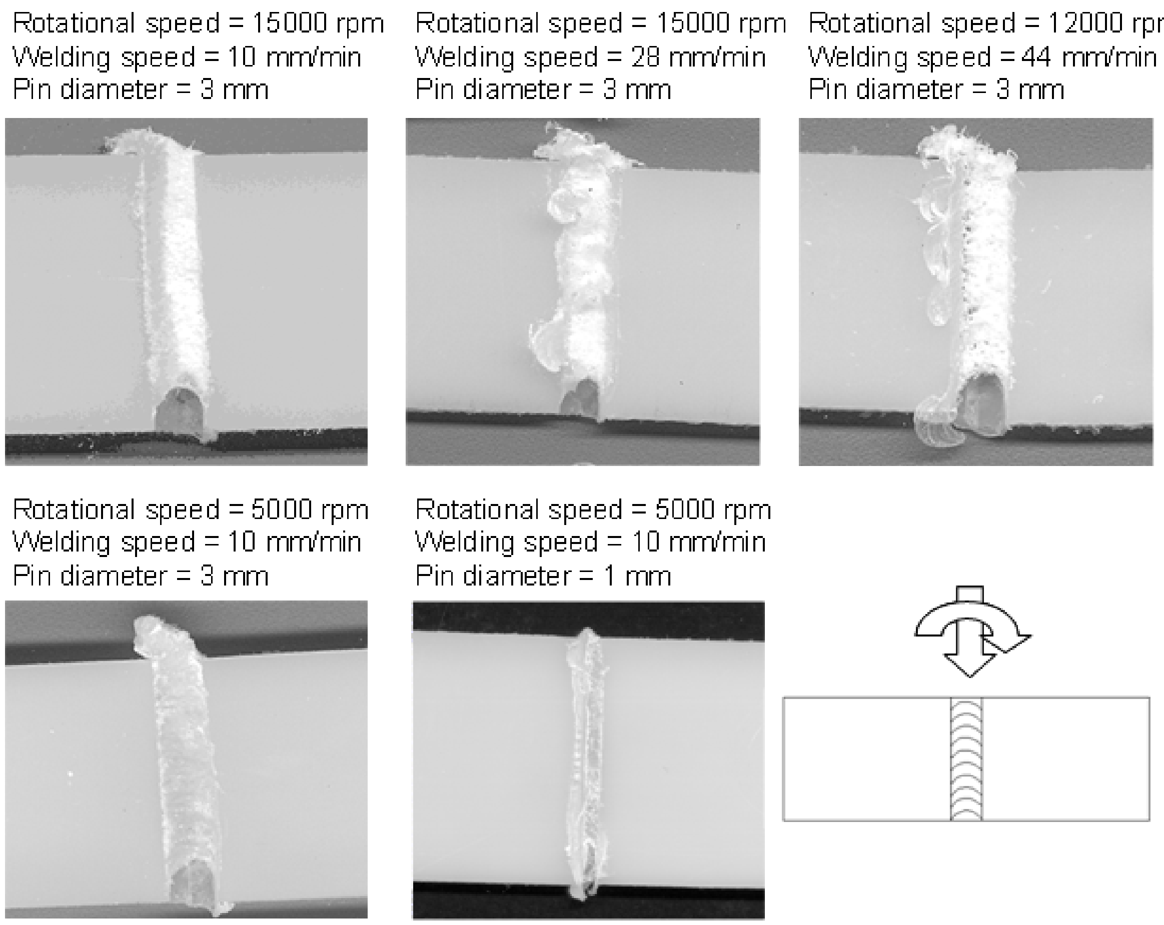

Fig. 1. Appearance of the welds

The mechanical behaviour of the joints was always different from the base material for all the experimented process conditions. In some cases, the joint strength was too low and it was not possible to perform the tensile test. Figure 2 shows a comparison between the tensile test of the HDPE sheet and a joint. The former is characterised by the typical ductility of HDPE whereas the latter is evidently brittle. However the maximum yield stress may be reached as well.

In order to investigate the effect of FSW process on the material properties of the processed HDPE, DSC tests were performed on samples extracted across the joint (fig. 3). The melting heat is directly related to the material cristallinity. It is evident that a lower crystal content is obtained into the bead due to the effect of the pin. Probably, due to the fast material tearing, the crystals are broken. Successively, after the pin pass, the material temperature is too low to allow the polymer to crystallise again.

Many process maps were prepared by using the experimental data as figs. 4 and 5 show. Figure 4a reports the tensile strength of the FSW joints at different welding speeds and rotational speeds. The joints were made at room temperature with the 1 mm diameter pin. For each feed rate, the best result was obtained at 6,000 rpm. In some cases, above this value, vibrations occurred due to the mechanical interaction of the samples and the pin. For this reason, a relative minimum of the tensile strength was observed between 5,000 and 10,000 rpm.

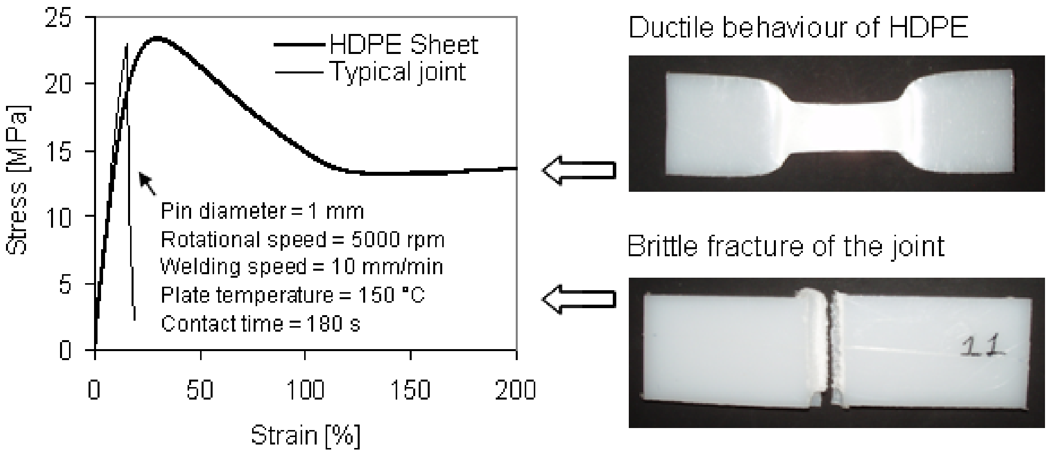

Fig. 2. Typical tensile tests on base material and FSW joint

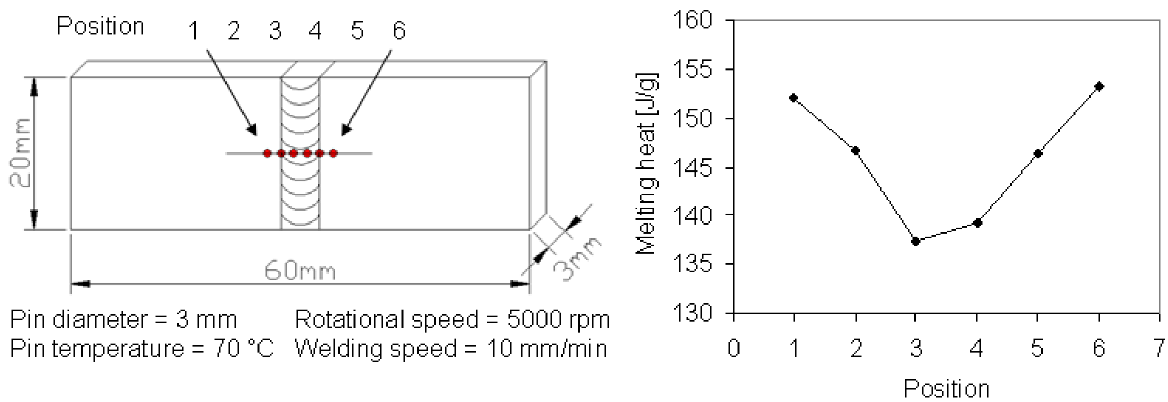

Fig. 3. DSC tests

In terms of feed rate, the best results were obtained at the intermediate value of 28 mm/min. This occurrence clearly shows that the process optimisation depends on the interaction of the process parameters. Figure 4b shows the same process map of fig. 4a in the case of the 3 mm pin diameter. Generally worst results were observed with the larger pin. The highest strengths were about 10 MPa, very far from the value of the base material (23 MPa, fig. 2).

In order to increase the joint strength and the process reliability, the pin was heated by means of a hot air gun (fig. 4c). The positive effect of the temperature was clearly visible for the 1 mm diameter pin, even if a clear trend of the tensile strength as a function of the rotational speed was not recognized. Moreover, higher strengths were observed for the minimum value of the feed rate. For the 3 mm diameter pin, the same procedure was followed: the pin temperature was set at 70°C. The welding speed was fixed to 10 mm/min and the rotational speed range was reduced. Even if the joint strength improved, a small increment was observed and the process repeatability remained poor.

On the basis of the discussed results, it was decided to fix the rotational speed at 5,000 rpm and the welding speed at 10 mm/min. Under these conditions, the effect of the temperature was deepened.

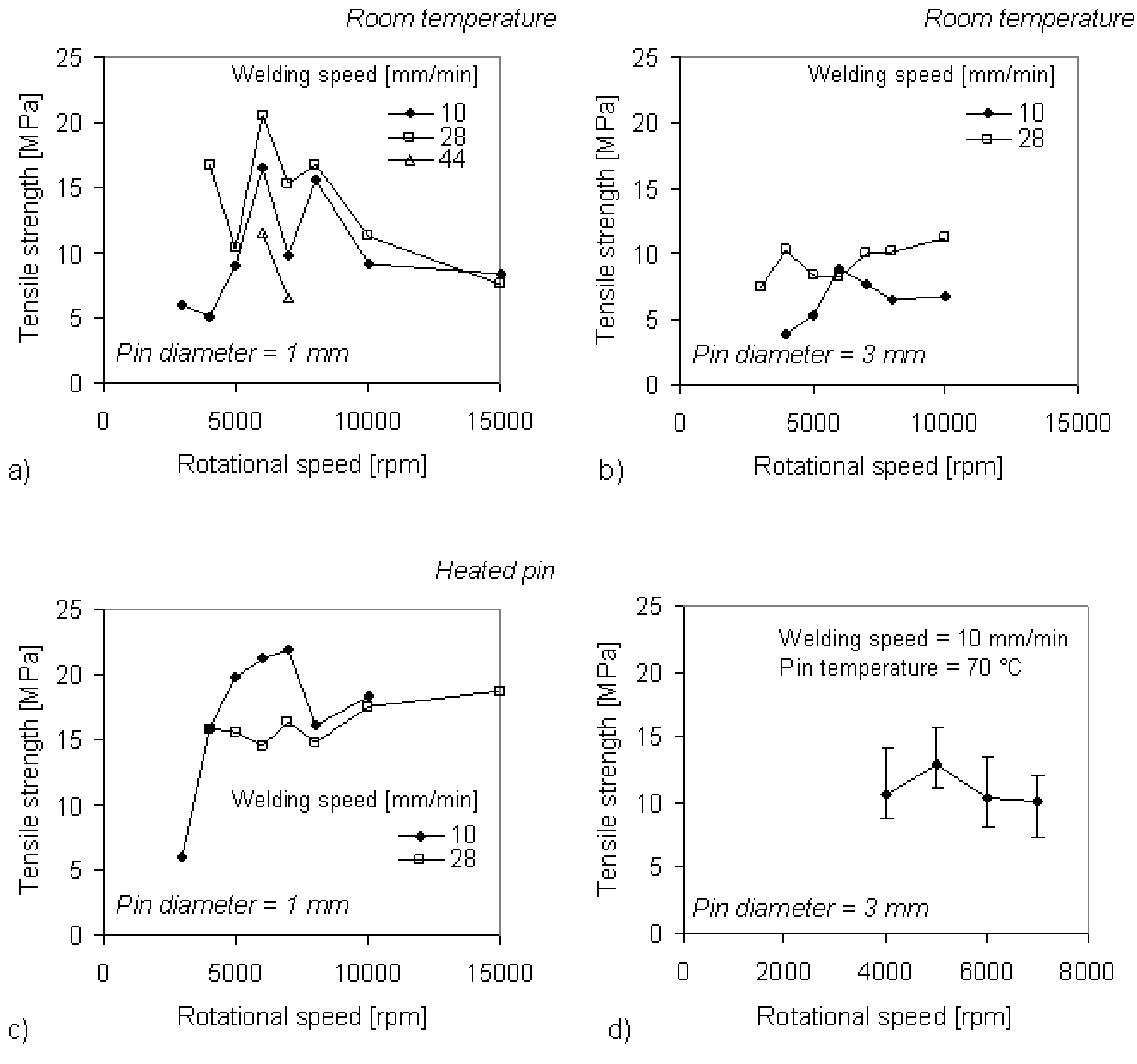

Fig. 4. Process maps

Figure 5a shows the joint strength in the case of the 3 mm diameter pin: the pin temperature was changed between 60 and 100°C. This experimentation was performed only by using the larger pin as the small pin rapidly cooled after the removal of the air gun. However the effect of the pin temperature is not able to overcome the negative effect of the pin size on the joint strength. For this reason, successive tests were carried out only by using the small pin. In order to increase the temperature during the FSW process, it was necessary to heat the HDPE samples rather than the pin. In this case, a heater plate was used and the HDPE samples were put in contact with the plate along the edge to join for a fixed time. Subsequently they were removed and positioned in the metal frame for the welding. Figure 5b shows the results for a plate temperature of 150°C and a contact time ranging from 0 to 180 s. Very high strengths were measured at high contact time, close to the value of the base material. A further comparison between the two pins is reported in fig. 5c for a plate temperature of 150°C. Even if the difference in the strength is evident, a positive effect of the sample temperature on the data dispersion is also evident for both pins. In the process map of fig. 5d, the plate temperature was changed together with the contact time. Unfortunately, the maximum contact time was not sufficient to obtain the high strengths discussed for figs. 5b and 5c. High contact times are necessary to give time to the sample to reach a sufficiently high temperature on the edge to join.

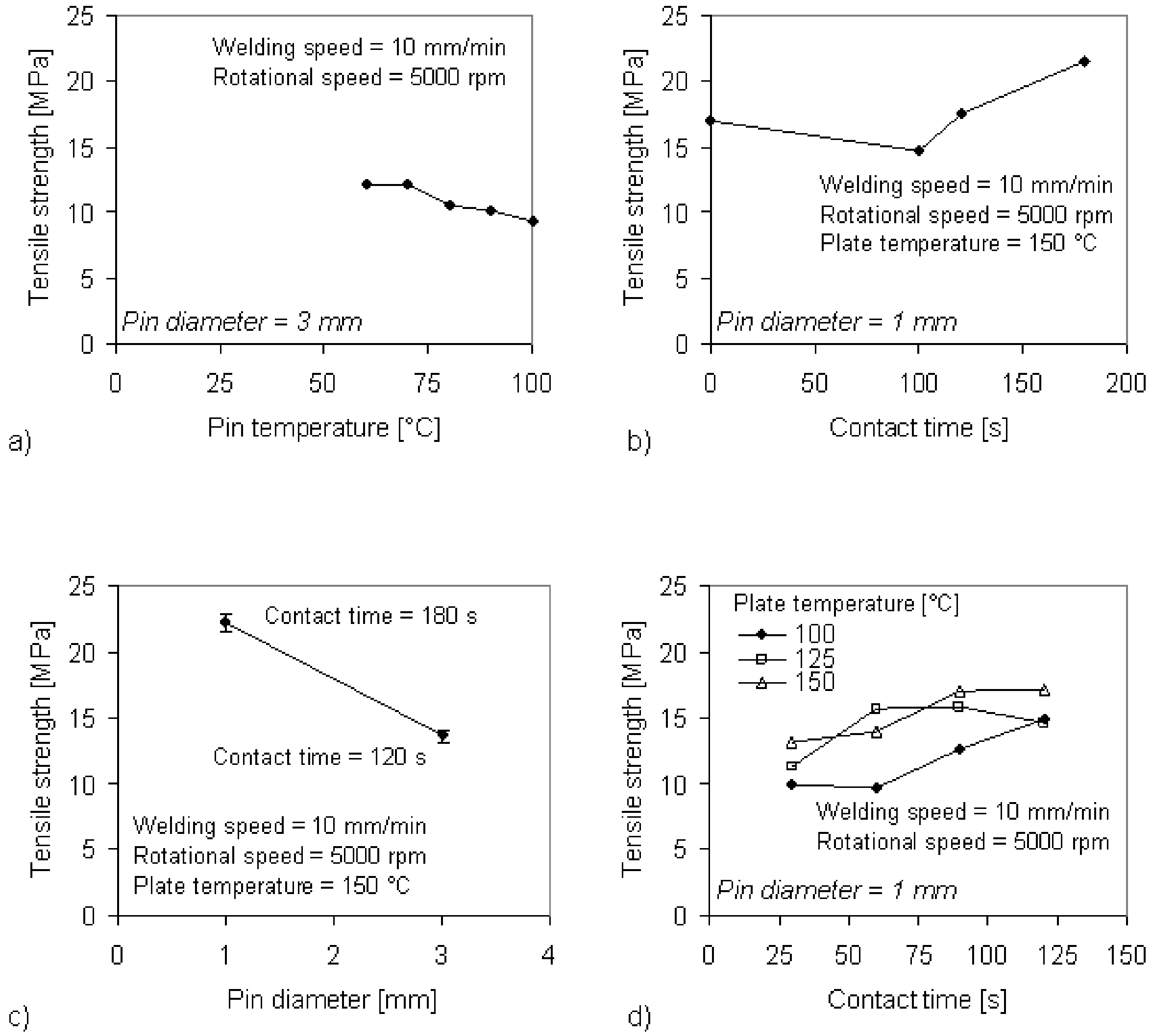

Fig. 5. Process maps

5. CONCLUSION

Friction stir welding (FSW) is a new solid-state joining technique, which was originally developed and successfully applied for aluminium alloys. Recently, attempts have been made to adapt FSW technology to the joining of thermoplastic materials; in many cases, the quality of the joints was inadequate because of a non-satisfactory homogenization, which led to an embrittlement of the joint. Therefore, FSW of plastics is not a ripe technology yet, even if it seems a promising technique because of some advantages over other joining technologies, as the low cost of machine and tooling cost. In such conditions very high strengths may be obtained (close to the strength of the base material) even if the process repeatability has to be improved. Heating the plastic material is a good way to make the process more robust. In the future FSW could be combined with the hot tool process to obtain higher joint performances.

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