An approach to weld dissimilar polycarbonate and high-density polyethylene by friction stir spot welding

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Received: 8 April 2022 / Accepted: 18 August 2022 / Published online: 23 August 2022 © The Author(s) 2022

Abstract

The friction stir spot welding of polymeric materials has been examined extensively; conversely, only a few researchers have addressed the friction stir spot welding of dissimilar polymers. In this study, the possibility of friction stir spot welding of dissimilar polycarbonate to high-density polyethylene is examined, which has not been previously investigated. The influence of welding parameters, namely, tool rotational speed and dwell time, was investigated experimentally, whereas the plunging depth, plunging rate, and tool geometry were kept constant during all tests. The induced temperature and the weld lap shear force were recorded and analyzed. Both materials are welded successfully by friction stir spot welding. At 2300 rpm and 40 s dwell time when the polycarbonate sheet was on the top, the maximum lap shear force of 0.37 kN was obtained. The findings demonstrated that an effective weld might be attained at a moderate frictional heating temperature slightly below the melting temperature \( T_m \) and glass transition temperature \( T_g \) of both welded materials. At very low temperatures, poor weld quality was obtained. When temperatures extensively increased, the results deteriorated to exhibit weak joint lap shear values because of the presence of cavities and pores in the weld junction.

Keywords Friction stir spot welding · Friction stir welding · Welding of polymers · Mechanical testing

1 Introduction

The rising demand for lightweight materials in the automotive and aerospace fields, particularly those having high strength-to-weight ratios, including polymeric materials and polymer composites, has attracted many researchers to conduct more studies on their properties and processing methods. Consequently, the joining of dissimilar polymers may open new horizons for new industrial applications that require the assembly or welding of various parts made of dissimilar or hybrid materials.

Several joining methods for similar and dissimilar materials have been examined previously, including mechanical fastening [1], adhesives bonding [2], mechanical clinching [3], friction stir welding, and friction stir spot welding (FSSW) [4]. Among these methods, the FSSW process demonstrated excellent weld strength compared with other welding techniques [4].

FSSW is a thermo-mechanical process that utilizes friction heating and stirring to produce a weld joint. The process includes a rotating tool that is plunged into the workpieces up to a prescribed plunging depth; the tool keeps rotating and stirring the material for a specific dwell time, and then, the tool retracts back out of the workpieces. Because of friction, heat is generated and transferred to the material, producing a weld joint at the workpiece’s interface during the stirring phase [5, 6].

FSSW of high-density polyethylene (HDPE) sheets was investigated experimentally; it was discovered that the rotational speed and dwell time are the most influential parameters on the weld strength [7]. At low rotational speed and moderate dwell times, the peak weld strength was obtained [8]. Among the various tool profiles, the tapered cylindrical pin exhibits the optimum weld strength with HDPE, whereas the straight cylindrical pin generates the worst strength [9]. Almost the same trend was discovered with polycarbonate (PC). The weld strength increases with dwell time up to 20 s, while it decreases with tool rotational speed. The weld strength was found to be very sensitive to the plunging rate, whereas preheating time has an insignificant effect [10]. Additionally, the pin dimensions and geometry affect
the PC’s weld strength, in which the weld strength is proportional to the shoulder diameter and decreases with pin diameter, or in other words, as the shoulder area increases (the area between the pin and shoulder tip), the weld area increases, and thus, the weld strength improves [11].

Several efforts have been made to enhance the welding process. A pinless tool with a circular gasket was examined during the weld of acrylonitrile butadiene styrene (ABS) sheets [12]. Welding in a water tank with a double pin tool and intermediate gasket was also studied [13]. The influence of novel tool profiles such as flat, triangular, and triflute profiles was also investigated on ABS [14].

However, the FSSW of dissimilar polymeric materials was investigated in a few publications only. The dissimilar welding of HDPE and polypropylene (PP) using FSSW was recently examined in two researches. The influence of tool rotational speed and dwell time on the weld strength was examined experimentally [15], and the process was performed at the range of 800–3500 rpm rotational speed and 40–120 s dwell time. Despite the immiscibility of both materials, the weld was conducted successfully, and when PP sheets were on the top, the optimum strength was obtained at moderate rotational speed and dwell time. Also, the weld of HDPE and PP was performed successfully in [8] over the range of 560–2400 rpm rotational speed and 30–120 s dwell time. Furthermore, the possibility of welding polymethyl methacrylate and ABS was examined experimentally [16]. The results reveal that the weld strength increased and then decreased with the tool rotational speed, and the optimum speed was 800 rpm; conversely, the weld strength increased with increasing dwell time up to 30 s.

In this study, the influence of rotational speed and dwell time on the FSSW weld strength of similar and dissimilar PC and HDPE was studied experimentally, and four different rotational speeds were used (800, 1400, 2300, and 3500 rpm), with three dwell times (40, 80, and 120 s). The temperature and maximum lap shear force were recorded and analyzed.

2 Experimental procedure

2.1 FSSW test samples

The test samples were prepared from commercial PC and HDPE sheets with thicknesses of 3 and 4 mm, respectively. The specimens were cut with a dimension of 101 × 24 mm, which matches the standard test specimen dimension specified in ASTM D3163.

2.2 FSSW test rig set-up

A conventional drill press is modified and used to conduct the FSSW process, as shown in Fig. 1. The drill spins with four different rotational speeds of 800, 1400, 2300, and 3500 rpm, while the vertical feed (plunging) is controlled by means of a specially designed and controlled mechanism, including a DC motor, gearbox, and microcontroller. The DC motor and the gearbox give the vertical forward and backward motion. Additionally, the microcontroller is dedicated to controlling the input voltage to the motor and hence provides the specified plunging rate, in addition to adjusting the required dwell time.

Furthermore, the specimens are placed on a specially designed wooden fixture, which in turn impedes the specimens’ axial and rotation motion and attains the required overlap between the specimens of 24 mm. A groove is prepared in the wooden fixture to carry a thermocouple for temperature measurement during the welding process. The thermocouple is laying under the center of the overlap area.

2.3 FSSW tool

The FSSW tool is fabricated from plain carbon steel with Rockwell hardness HRB 92.3. The tool has a tapered shape with pin length and diameter of 5.5 and 7.5 mm,
respectively, and a shoulder diameter of 18 mm. The tool’s tapper and concavity angles are 15° and 6°, respectively, as shown in Fig. 2.

2.4 Test technique

The welding process may be subdivided into three main phases, namely, plunging, stirring, and retracting. The plunging process is performed by moving the drill crosshead with the prespecified plunging rate of 15 mm/min downward toward the workpieces; the rotating tool keeps moving until the required plunging depth is achieved, which is 5.5 mm; then, the plunging motion stops, and the stirring phase starts for the designated dwell time. Three dwell times are selected in the present study, namely, 40, 80, and 120 s. Then, the retracting phase starts, moving the tool out of the workpiece. During the whole test, the resulting temperature at the center point of the overlap area at the bottom of the lower workpiece was recorded using a K-type thermocouple.

2.5 Test parameters

The test includes a variation of the two primary welding parameters: the rotational speed and the dwell time, while the plunging rate was kept constant during all tests. Table 1 summarizes the welding parameters.

2.6 Test measurements

Four replicates of each weld process were tested under lap shear configuration. The ultimate lap shear forces were determined and recorded using WDW 300 computer-controlled electronic universal testing machine, with a crosshead speed of 1.27 mm/min (0.05 inch/min) according to ASTM D3163.

2.7 Microstructure investigation

To examine the microstructure and surface topology of selected specimens, TESCAN VEGA 3 scanning electron microscope (SEM) was used. The specimens were first prepared by coating with gold inside a turbomolecular pumped coater Quorum Q150T ES.

2.8 Base material specification

To identify the base material properties, a series of tests were conducted on both PC and HDPE sheets. Differential scanning calorimetry (DSC131 Evo SETARAM) was used to measure the actual glass transition temperature ($T_g$), melting temperature ($T_m$) for PC sheets, and $T_m$ for HDPE. Additionally, the melt flow rate (MFR) and the melt density ($\rho_m$) were tested by Zwick Roell Mflow plastometer; the tests were conducted at 2.16 kg/190 °C and 2.16 kg/260 °C for HDPE and PC, respectively, according to ASTM D 1238. The base materials’ tensile strength was tested according to ASTM D638 using WDW 300 universal welding parameters.

### Table 1 Experimental welding parameters

| Welding parameter   | Unit | Value       |
|---------------------|------|-------------|
| Rotational speed    | rpm  | 800, 1400, 2300, 3500 |
| Dwell time          | s    | 40, 80, 120  |
| Plunging rate       | mm/min | 15          |
| Plunging depth      | mm   | 5.5         |
testing machine. Table 2 summarizes all the obtained material properties.

| Property                        | Unit   | Value  |
|---------------------------------|--------|--------|
| Density ($\rho$)                | g/cm³  | 0.974  |
| The density of melt ($\rho_m$)  | g/cm³  | 0.72   |
| Melt flow rate (MFR)            | g/10 min | 0.93   |
| Melting temperature ($T_m$)     | °C     | 139.9  |
| Glass transition temperature ($T_g$) | °C | --- |
| Tensile strength               | MPa    | 20.68  |

### 3 Results and discussions

In this study, the influence of both tool rotational speed and dwell time on the weld’s lap shear strength of dissimilar welded PC and HDPE sheets has been studied experimentally.

Preliminary, the base materials were welded similarly by FSSW to investigate the ranges of variation of the weld strength of materials as a function of the weld parameters, and to compare the strength of welding the dissimilar materials with that of the similarly welded base material.

#### 3.1 Influence of process parameters on the weld of similar PC sheets

Figure 3 depicts the effect of the process parameters on the average values of the lab shear forces during the FSSW of similar PC sheets. The curves show that the lap shear force is inversely proportional to the tool rotational speed while slightly increasing with the increase of dwell time. This may be explained by increasing the dwell time, sufficient stirring, and mixing the materials takes place, which increases the friction heat transferred to the workpieces, and the weld strength enhances. While by increasing the rotational speed, high inertia force is generated and acts to increase the ejected material from the weld zone to outside the weld area, and thus, the material in the weld zone is reduced, and consequently, the weld area and weld strength deteriorate. The same findings were reported previously in [10].

Accordingly, the optimum weld strength for PC sheets was obtained at a low rotational speed (800 rpm) and high dwell time (120 s).

#### 3.2 Influence of process parameters on the weld of similar HDPE sheets

Figure 4 reports the effect of tool rotational speed and dwell time on the lap shear strength of similarly welded HDPE sheets. During the weld of similar HDPE at low rotational speeds (800 and 1400 rpm), the frictional heat generated increases with increasing the rotational speed and dwell time up to 80 s, and hence, good mixing and stirring occur between both workpieces, leading to proportional weld strength, whereas the weld strength slightly decreases at higher dwell time, which may be ascribed to the increase of the quantity of extruded material from the weld zone leading to a decrease in the weld area and thus the weld strength slightly decrease.

However, at higher rotational speeds (2300 and 3500 rpm), and due to the increase of inertia force and the quantity of extruded material, the material separates from the workpieces and sticks to the tool pin, producing a plastic ring, as shown in Fig. 5; the ring functions as a thermal isolator between the rotating tool and the HDPE workpieces; and thus, a reduction in the frictional heat takes places, and subsequently, the weld strength fails.

Now, it could be observed from the above results of the similar weld of PC and HDPE that the highest lap shear force during welding of PC and HDPE were 1.6 kN obtained...
at 800 rpm and 120 s dwell time and 0.915 kN obtained at 1400 rpm and 80 s dwell time, respectively.

3.3 Influence of process parameters on the dissimilar weld of PC and HDPE sheets

PC and HDPE were welded for the first time by FSSW to investigate the feasibility of the welding technique on both materials. The investigation includes the weld of both dissimilar materials, first when PC was on top and HDPE on the bottom (PC to HDPE) and then when HDPE was on top and PC on the bottom (HDPE to PC). The variation of induced temperature during the process and the weld’s lap shear strength were recorded and illustrated in Figs. 6 and 7 for PC to HDPE and in Fig. 13 for HDPE to PC, respectively.

The resultant strength is lower than that of the similarly welded base material, especially in comparison with PC. This is due to the fact that each material has a different range of $T_g$ and $T_m$, in which the HDPE reaches its complete melting, while PC is still in the solid form, and thus, an incomplete bonding takes place between molten HDPE and solid PC material.

The above results conclude that the weld strength is highly dependent on both process parameters and the resulting process temperature. By correlating the temperature curves, in Fig. 7, with the obtained values of lap shear forces in Fig. 6, it could be observed that the higher strength is obtained during the solid-state welding process, or in other words, at temperature ranges below the melting temperatures of both materials. When the temperature increases and exceeds the $T_m$ of HDPE (the lower workpiece), a molten material exists in the weld region, and during the material’s cooling and solidification, the material shrinks, leaving cavities and pores. This porous structure results in high residual stresses in the material, resulting in a reduction in the weld strength.

The results may also be investigated using macroscale observation. At low rotational speed, e.g., 800 rpm, the quantity of frictional heat generated leads to low process temperature. At this temperature range, both materials are entirely in a rigid solid form, and thus, the plunging and stirring process acts to press the upper sheet toward the lower sheet, as shown in Fig. 8, without any mixing or bonding between both materials, and thus, weak weld joints are produced.

At rotational speed of 1400 rpm and 40 s dwell time, a small but homogenous weld area was formed due to the better stirring in consequence of the higher speed. By increasing the dwell time to 80 s, the temperature increases reaching the $T_g$ of PC and exceeding the $T_m$.
of HDPE, leading to the presence of molten material in the weld zone. Because of these reasons, some irregularities and cavities were observed in the weld zone. These irregularities function as residual stress risers in the weld zone. By increasing the dwell time to 120 s, the HDPE and PC workpiece exceeds their \( T_m \) and \( T_g \), respectively. Thus, a soft–molten region occurs below the tool. A significant quantity of the molten material sticks to the sample fixture, resulting in excessive material loss and separation from the weld zone. For these reasons, the lap shear force decreases with increasing dwell time. Figure 9 depicts the weld area shape’s development with dwell time at 1400 rpm.

Figure 10 depicts the weld zone shape during welding at 3500 rpm, which is almost similar to that of 2300 rpm. At these rotational speeds and 40 s dwell time, higher heat is generated than that reached with 800 and 1400 rpm, by which the process temperature is slightly below the \( T_m \) of HDPE and \( T_g \) of PC, so both materials are in the softened state. Because of the material softening, big and homogeneous weld rings are produced, resulting in a strong joint between the upper and lower workpieces, and thus, high lap shear forces were obtained. When the dwell time increases to 80 and 120 s, the process temperature exceeds the \( T_m \) and \( T_g \) of HDPE and PC, resulting in the occurrence of irregularities, cavities, and pours in the weld area, and then, the molten material sticks to the sample fixture leading to the material’s deterioration in the welding zone, and material separation occurs. For this reason, the weld strength fails at higher dwell times.

Furthermore, the microscale investigation shows the same findings; samples of 1400 rpm and 40 s dwell time and 3500 rpm and 40 and 120 s dwell times were scanned using SEM. Figure 11a shows the microstructure at 1400 rpm; both materials are clear, and the weld morphology seems to be very homogeneous, whereas the weld junction’s thickness is very thin and almost not seen. By increasing the magnification, it could be noted that the structure is clear of any voids or cavities, as shown in Fig. 11b.

Figure 12 shows the microstructure of welded samples at 3500 rpm; in the case of 3500 rpm at 40 s, the sample structure is also clear from any cavities or irregularities, and the weld junction thickness is also higher than that obtained at 1400 rpm, with a thickness of approximately 500 µm. Conversely, at 3500 rpm and 120 s, due to the excessive heating and the complete melting of the HDPE, and the PC workpiece comes to a region very near to its complete melting, an irregular structure was noticed, with excess cavities and voids. For this reason, the lap shear strength deteriorates and reaches less than a quarter of the values obtained at 40 s.

Generally, it may be concluded that the efficient welding condition may be obtained at moderate process...
temperatures slightly below the $T_m$ or $T_g$ of both welded materials. Also, the excessive dwell time and rotational speed lead to highly deformed material and hence low weld strength.

Welding of HDPE to PC (HDPE workpiece at the top and PC at the bottom side) was unsuccessful except with 2300 rpm and 120 s and 3500 rpm and 80 and 120 s with average maximum lap shear force of 0.045, 0.15, and 0.115 kN, respectively. The obtained weld strength was very weak compared with the weld strength of both base materials and with that of dissimilar weld of PC to HDPE, wherein the maximum weld strength is approximately one-third of the peak weld strength obtained in welding PC to HDPE and approximately 10% and 15% of the peak weld strength of similarly welded PC and HDPE, respectively. Otherwise, the specimens directly break during the removal from the wooden fixture. Analyzing the process temperature in Fig. 13, it was evident that when the HDPE workpiece was on top, the temperature was extremely low, below the $T_g$ and $T_m$ of PC and HDPE, respectively. Since almost all the area of the tool pin and shoulder are in contact with the upper workpiece, HDPE, and due to the fact that the dynamic friction coefficient between steel and HDPE is very low [17], the process temperature is much lower than that when the PC sheet was on top. This indicates that inadequate frictional heat is generated and transferred to the materials, and consequently, no softening takes place, and hence, a weak bond is obtained.

At high rotational speed and higher dwell time, 2300 and 3500 rpm, the PC workpiece experiences severe friction with the rotating tool, leading to a tip formation at the interface region, as shown in Fig. 14. Additionally, the figure shows that there is no any softened or pasty material found during the weld of HDPE to PC at 3500 rpm, and the formed joint is due to the presence of the tip in the PC workpiece, which interlocks with the upper HDPE workpiece without any bonding.

The tip was only formed at 2300 rpm and 3500 rpm. The load-bearing of the interlocking tip is of very low order, leading to a very low weld strength.
Fig. 10  Weld zone shape at 3500 rpm: a 40 s, b 80 s, and c 120 s. Note: All the left-hand side specimens are the lower workpiece (HDPE), and the right-hand side is the upper workpiece (PC).

Fig. 11  SEM images for welded samples at 1400 rpm and 40 s: a 50× magnification and b 250× magnification.

Fig. 12  SEM images for welded samples at a 3500 rpm and 40 s and b 3500 rpm and 120 s.
Conclusion

As an output of the conducted experiments, the following can be concluded:

– PC specimens were welded successfully to HDPE by FSSW technique within the range from 800 to 3500 rpm and 40 to 120 s dwell time. Additionally, when HDPE was on top and PC was on the bottom, the weld was very weak at 2300 and 3500 rpm and unsuccessful with 800 and 1400 rpm. However, the optimum welding conditions for PC to HDPE and HDPE to PC were 2300 rpm and 40 s and 3500 rpm and 80 s, respectively. Extreme heating of the specimens over their melting temperature increases the material’s porosity and reduces the weld strength.

– The primary factors governing the weldability of dissimilar polymers other than the operating parameters are the material’s characteristics (melting temperature \(T_m\) and glass transition temperature \(T_g\)), the coefficient of friction, and the position of the welded polymers on each other.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Availability of data and materials Not applicable.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication The author confirms
That the article has not been published before,
That the article was revised without consideration for publication elsewhere,
That its publication has been approved by all co-authors,
All authors agree to publication in this journal.

Competing interests The authors declare no competing interests.

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Fig. 13 Temperature variation during dissimilar weld of HDPE to PC

Fig. 14 welded samples of HDPE to PC at 3500 and 120 s dwell times. Note: The left-hand side specimen is the lower workpiece (PC), and the right-hand side is the upper workpiece (HDPE)

4 Conclusion
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