Experimental Study of the Feasibility of Friction Stir Spot Welding in Polyethylene

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Abstract

Friction stir spot welding (FSSW), as a solid state joining process, shows great potential to be a replacement of single-point joining processes. However, the possible application of FSSW in polymers needs more attention. In the present paper, experimental studies have been conducted to explore the feasibility of welding polymers by FSSW. The investigation is applied on the most popular polymer, the polyethylene (PE), under different operating conditions. Plunging depth, and dwell time at two different tool rotational speeds have been taken as varying parameters. The effect of the welding parameters on the strength of welded joints has been determined by lap shear test. The temperature in the welding material zone during dwell time has also been recorded to investigate the effect of the duration of dwell time on the heat generation during welding.
The results confirm that FSSW can be applied to PE and that the tool rotational speed, plunging depth, and dwell time are important in the joint formation and its strength.

Keywords:
polyethylene, friction stir welding, friction stir spot welding, dwell time, lap joints, lap shear test

Introduction

Polymers are widely used in many engineering applications as automotive, electronics, packaging and aerospace [1, 2].

There are three major methods for joining plastics: mechanical fastening, adhesive and solvent bonding, and welding. Welding is the most effective method of a permanent plastic joint [3].

Polymers welding can be divided according to heat transfer mechanism into three methods: heat conduction, process based on heat radiation and friction welding [4].

Friction stir welding (FSW) process has shown to be a successful welding technology for joining metals [5]. It is used for joining different types of similar and dissimilar materials such as aluminum and its alloys, copper, mild steel, zinc, lead – magnesium alloys and metal matrix composites based on plastic [6]. Recently, FSW is used as a new method of joining polymeric materials.

The basic concept of FSW is a non-consumable rotating tool inserted into materials to be joined. Friction between tool and workpiece generates heat which welds the two sheets together.

Friction stir spot welding (FSSW) is a FSW method in which there is no linear movement during joining. FSSW consists of four phases: preheating, plunging, stirring and waiting before retracting [7, 8]. The FSSW process can be summarized as follows: Rotating and forcing a special tool to penetrate a lap joint for a given pre-heating dwell time until the tool reaches the predetermined plunge depth whilst the tool rotational speed continues (consolidation) for a prescribed dwell time.

Consequently, the material underlying and surrounding the tool is heated and softened as to be stirred by the tool. Then, the tool rotational speed is stopped and the tool is maintained at the joining depth for a certain waiting time in which tool shoulder compresses the underlying material to form the spot joint, and then the tool is retracted.

Preliminary results have shown that the weld strength in FSSW is comparable to other available welding techniques, while joining time is equal or shorter and with less power consumption [9].

The factors controlling the quality of FSSW have been studied. It was found that the main factors were the tool geometry and material, the specimen thickness and the process parameters (namely: the tool plunge depth, the rotational speed, the dwell time, the plunging rate and the waiting time) [10].

The dependence of the lap shear fracture load on the FSSW parameters (rotational speed, plunge depth, dwell time), different tool materials (stainless steel, steel, aluminum and copper) and tool geometry (cylindrical, inverse tapered, triangular, tapered pins with different shoulders such as convex and concave shoulder) have been investigated. It was found that the welding parameters have very significant effects in FSSW joining and playing an important role in the heat generation and in the solidification period of the FSSW process [11, 16].

The experimental and numerical study of FSSW of high density polypropylene proved that dwell time, rotational speed and tool plunge depth were the most effective parameters on the strength of the welded joints [8]. The tool plunge rate showed no effect on FSSW of polypropylene [16].

The influence of speeds and dwell times on the mechanical properties of polycarbonate sheets was analyzed and it was seen that dwell time and waiting time, plunge depth have the most important parameters on joint strength but the tool rotational speed and pre-heating time have lower effect on the mechanical behavior of FSSW joints. The pre-heating time showed negligible effect on mechanical behavior of FSSW joints of polycarbonate sheets [17].

Due to the insufficient experimental data on polymers FSSW processes, the present experimental investigation is an endeavor towards assessing of finding out the optimum FSSW parameters in joining polymeric materials. By way of example, PE sheets have been, herein, investigated for possible industrial applications.

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Experimental work

The present research focuses on the effect of the welding parameters controlling the FSSW on the strength of polyethylene joints. These parameters comprise mainly the plunging depth, and dwell time at different tool rotational speed whilst keeping constant tool geometry and material as well as plunging rate and waiting time.

Specimen preparation

In the conducted experimental work, the FSSW was performed on a commercial polyethylene. Each lap joint specimen consisted of two sheets cut by a cutter machine (STAR 640) with dimensions of 25 mm width, 101.6 mm length and 4 mm thickness. The two sheets were welded with overlap of 25 mm in length, according to the ASTM D 3163 standard as shown in Fig. (1).

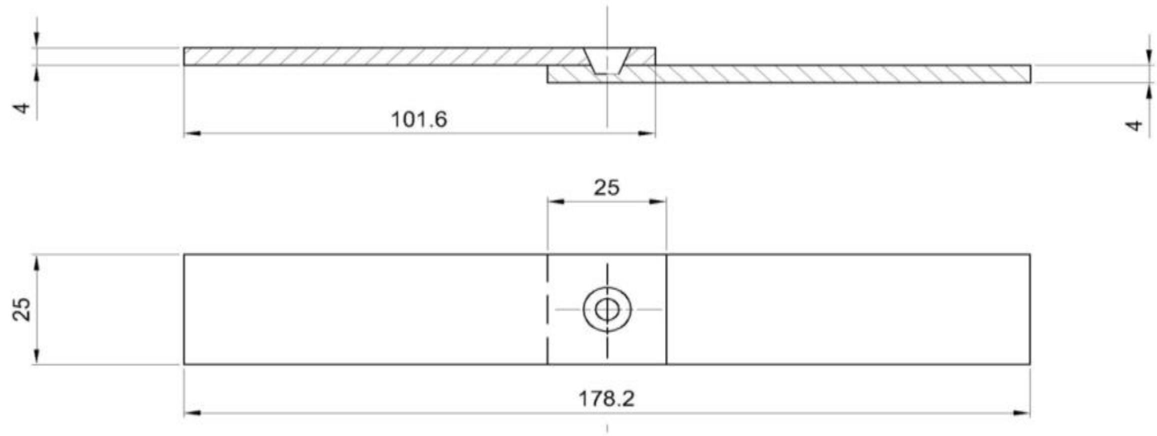


Fig. 1 FSSW test specimen

Experimental setup

A standard milling machine was set up with a special clamping fixture and used in conducting the welding processes, as shown in Fig. (2).The tool was tapered cylindrical pin 5 mm in diameter and 5.5 mm in length with taper angle $15^{o}$and shoulder 10 mm in diameter with concavity angle 6^{o}, machined from HSS [14], Fig. (3).

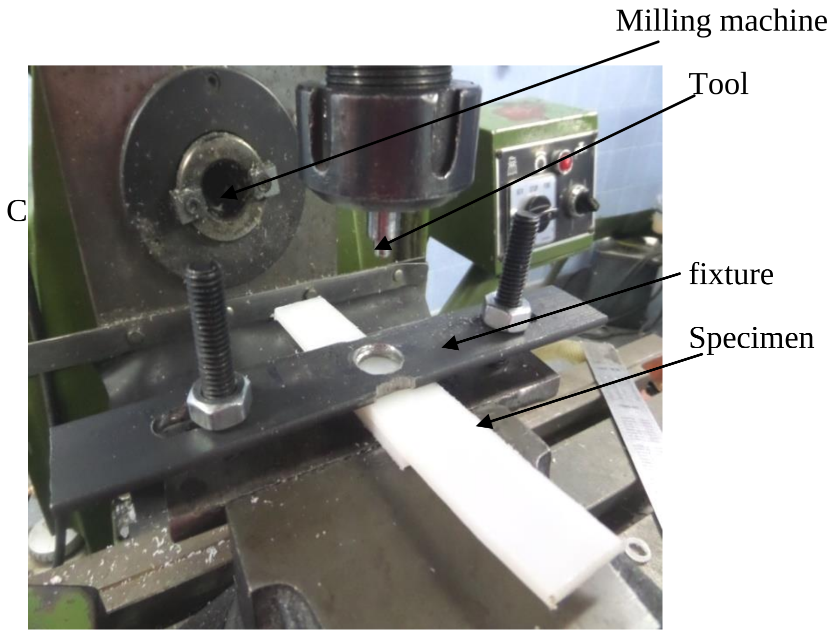


Fig. 2 Experimental set up

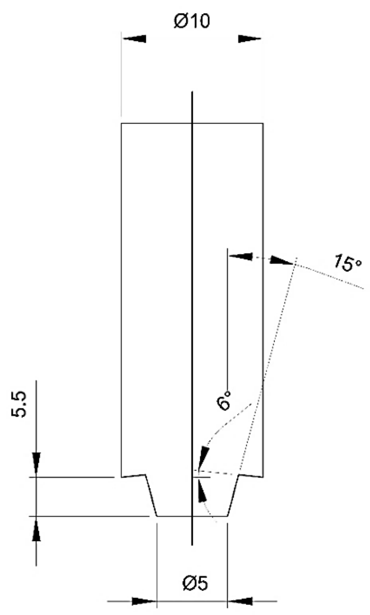


Fig. 3 Tool geometry

Test measurements

The plunging force was measured with an S-shape load cell model (LFS 210) placed under the specimen, Fig. (4a, 4b)

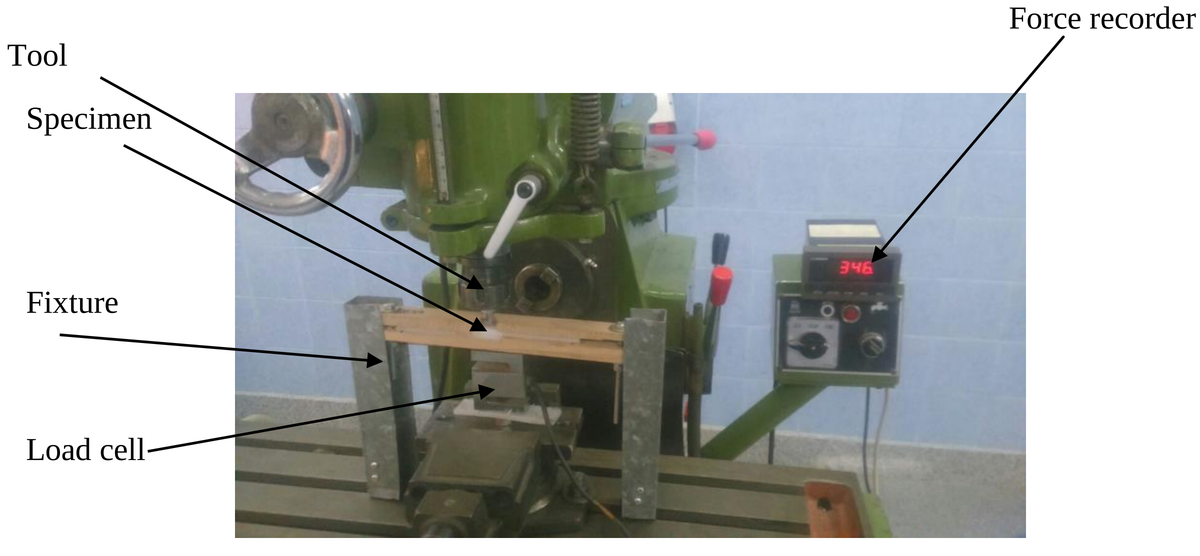


Fig. 4 (a) Force measurement set up

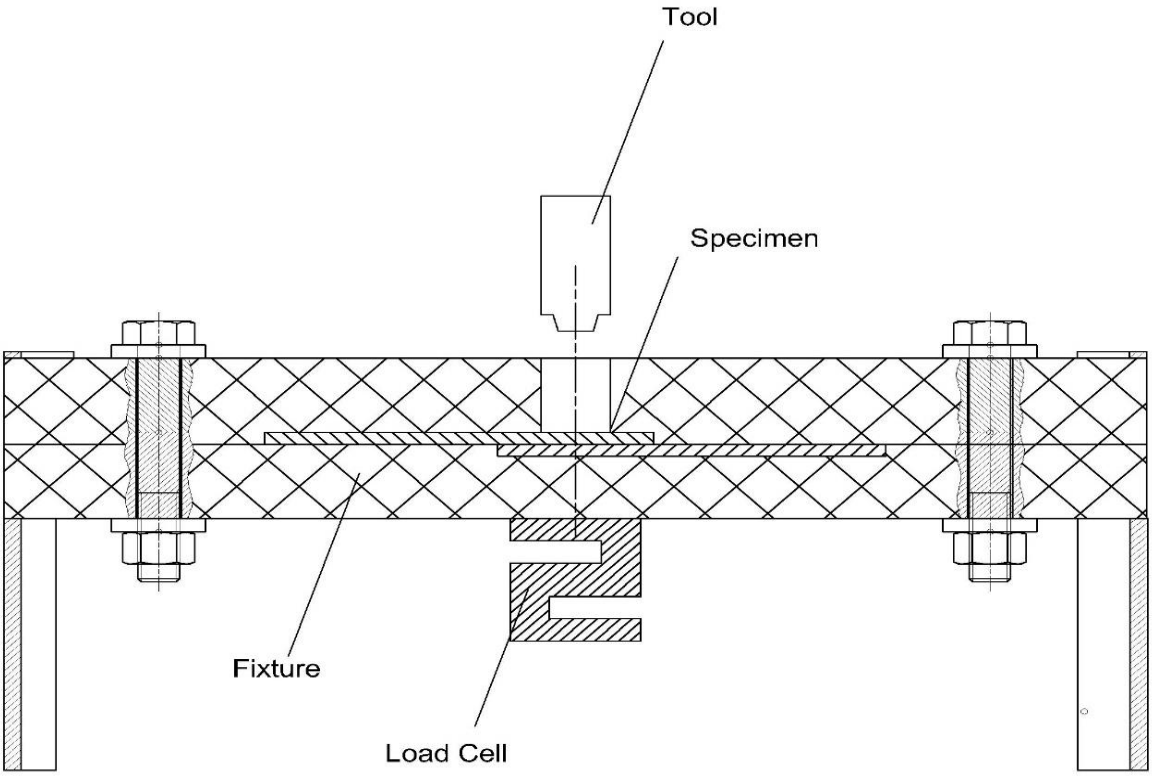


Fig. 4 (b) Sectional view for force measurement set up

An infrared K type thermometer (IR 900-30S) was used to measure the temperature at the end of the dwell time.

The tool was retracted immediately at the end of the dwell time and then the temperature was recorded.

The lap shear test of the welded specimens was carried out using model (WDW-300) universal testing machine as shown in Fig. (5) with constant cross head speed of 1 mm/min according to ASTM D 3163.

Test procedures

A preliminary test was done to determine the range of parameters variation and the tested parameters were as follows:

The plunge depth was varied from 5 mm to 6.5 mm with dwell time 40 s and plunge rate 30 mm/min and at tool rotational speeds 2050 and1350 rpm.

The dwell time, in which the tool continuous to rotates on the spot of the joint with no movement or no further plunge of the tool, i.e. during the stirring, was varied from 20 s to 90 s with plunge depth 5.5 mm and 30 mm/min plunge rate at tool rotational speeds 2050 and1350 rpm.

The lap-shear strength was obtained from testing three individual specimens, welded with identical welding parameters.

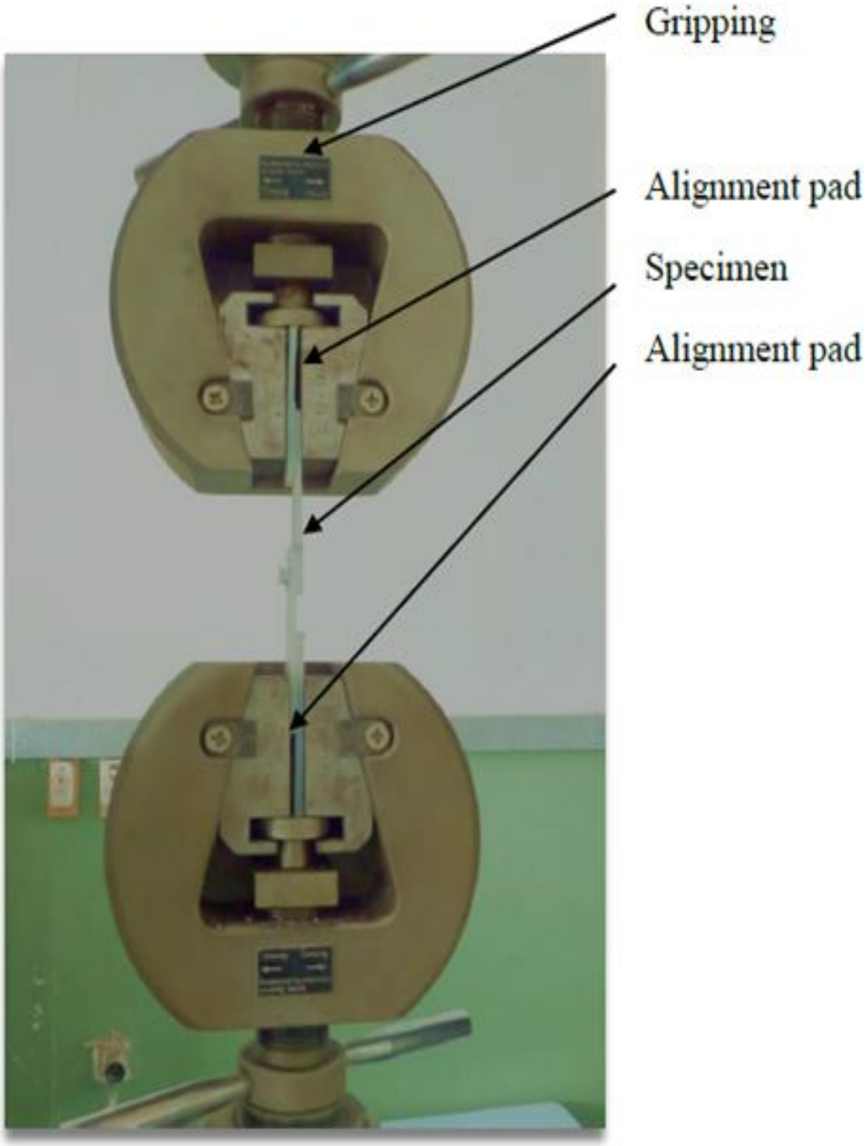


Fig. 5 Lap shear test

Results and discussion

From the analysis of the plunging force variation with time, Fig. (6), it can be seen that the force is zero before plunging and increases during plunging reaching its maximum value of about 1780 N. Then, the force decreases during stirring to almost zero and becomes negative as the tool is retracted due to friction between soft material and tool tip.

Thermal interaction is a very important aspect in FSSW since the technique relies on the heat generation due to friction between the tool and work piece which leads to softening and joining process.

As the heat generation depends mainly on the welding parameters and the tool geometry, the present work focuses on the effect of the main welding parameters on the welding quality.

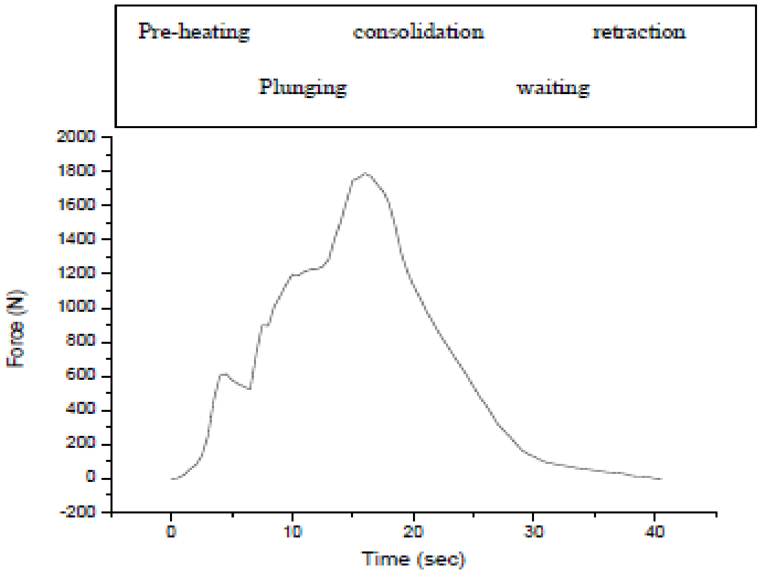


Fig. 6 Plunging force during FSSW.

In the present investigation, tests were arranged to cover the effect of welding parameters on the lap-shear strength of the welded joints. The shape of an exemplary lap welded joint is shown in Fig. (7). The joint is characterized by a nugget with its dimensions being related to the tool shape. At the top of the nugget, a spiral shaped extruded polymer is presented. The joint strength, nugget configurations and extruded polymer are dependant of the welding parameters as will be, herein, discussed.

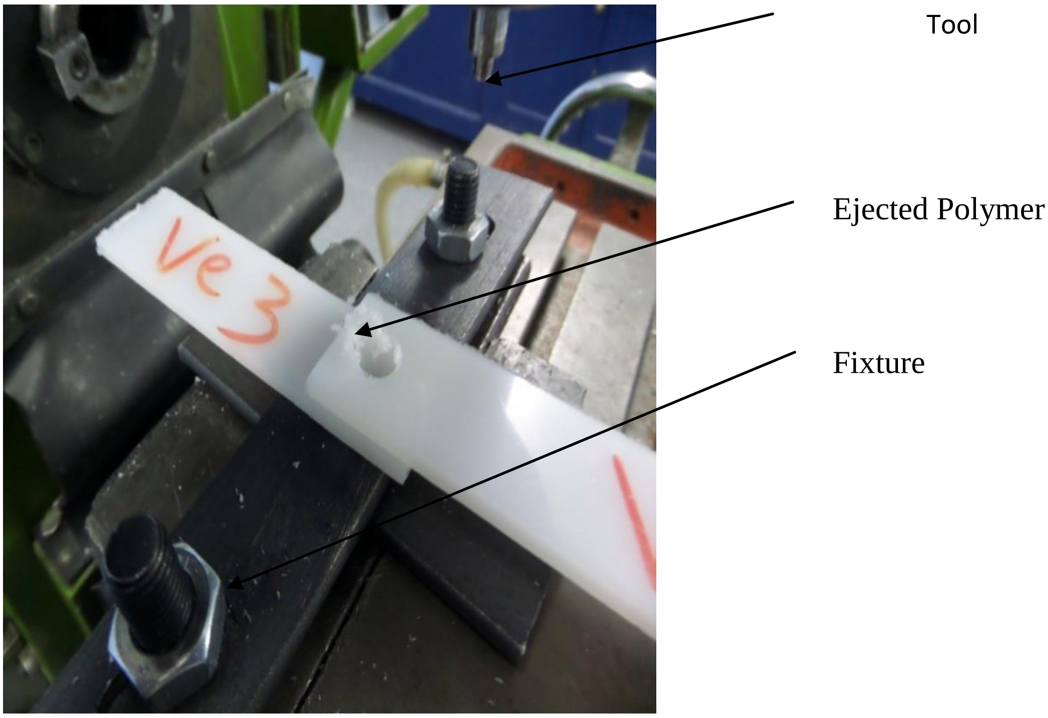


Fig. 7 Welded joint configurations

Effect of plunging depth

The effect of plunging depth on the lap shear force for the welded specimens is shown in Figs. (8, 9).

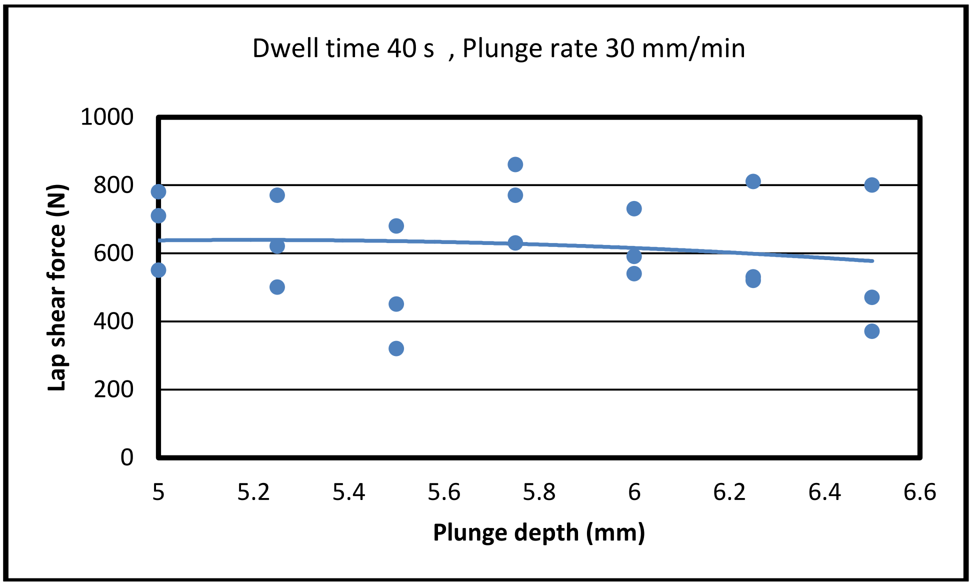


Fig. 8 Effect of plunging depth on lap shear force at tool rotational speed 2050rpm

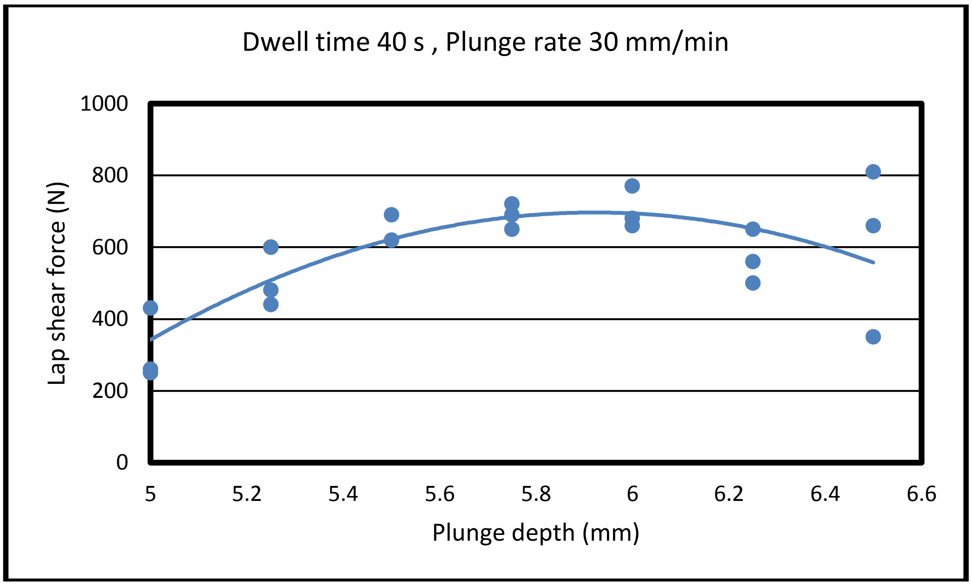


Fig. 9 Effect of plunging depth on lap shear force at tool rotational speed 1350rpm

It can be seen from the results presented in Figs. (8, 9) that the lap shear force increases to a maximum value at 5.75 mm plunging depth with rotation speed 2050 rpm and at 6 mm with rotation speed 1350 rpm. This can be explained as increasing the plunging depth increases the tool pressure which creates high heat generation in the weld zone leading to big bond area and thick nugget. The followed decrease in the lap shear force may be attributed to the extra thinning of the upper sheet as previously suggested [18].

The effect of dwell time

The effect of dwell time on the lap shear force for of the welded specimens is shown in Figs. (10, 11).

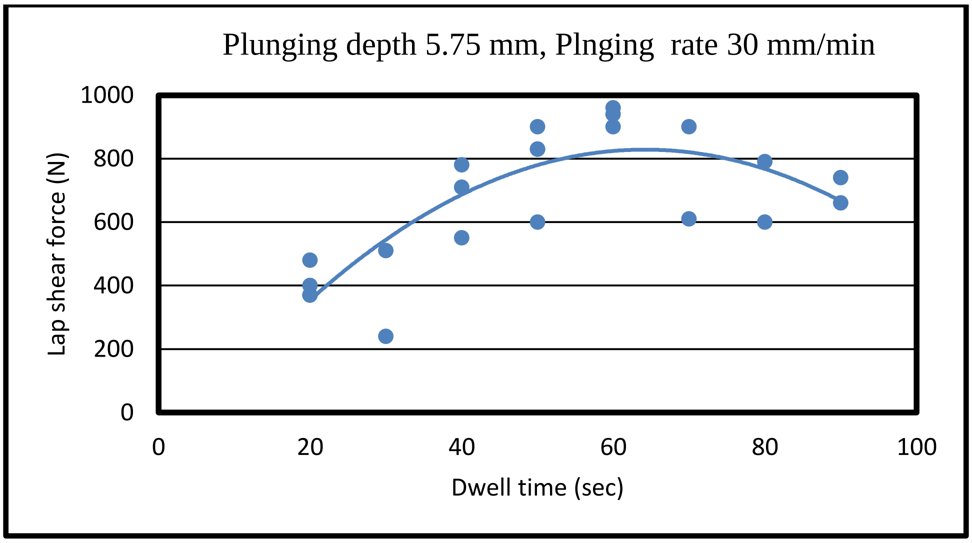


Fig. 10. Effect of dwell time on lap shear force at tool rotating speed 2050 rpm

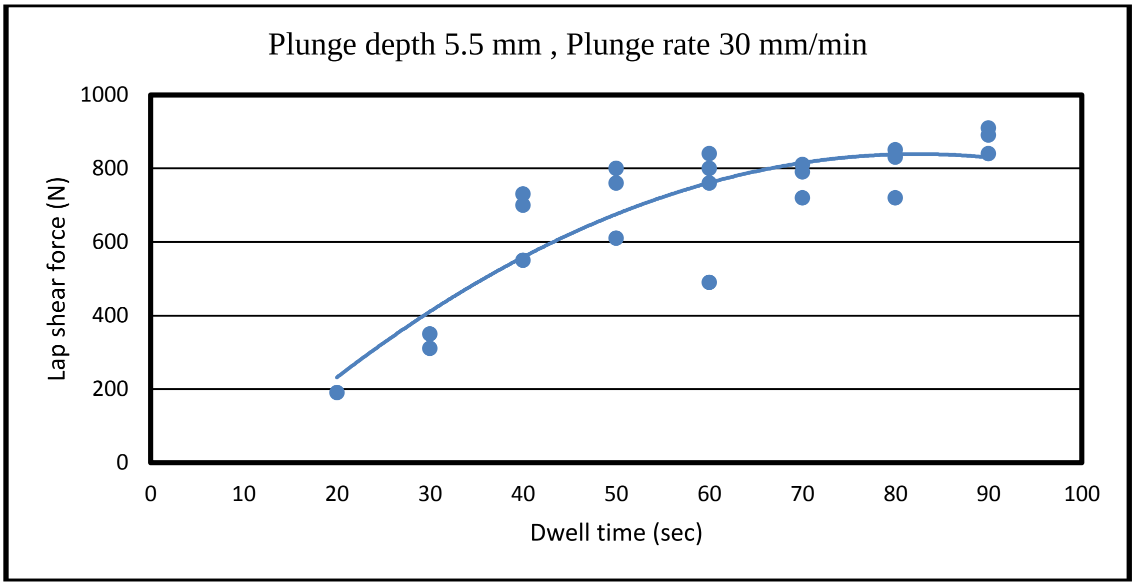


Fig. 11 Effect of dwell time on lap shear force at tool rotating speed 1350 rpm

As the dwell time is responsible of the melting of the polymeric material due to the stirring of the material, dwell time is the most effective parameter for weld strength. A longer dwell time induces large amount of heat generation and a large welded area due to the large time of the tool rotation and friction heat between the tool and the work piece [19]. It can be seen from Figs. (10, 11) that the maximum lap shear force is obtained at dwell time 60 s for 2050 rpm and 80 s for 1350 rpm. This variation of lap shear force with time is due to that long dwell time helps the heat generation and material mixture, but extreme dwell time can cause material extrusion and cavity generation which agree with previous findings [20].

The effect of dwell time on the measured temperature at the welding zone is presented in Fig. (12).

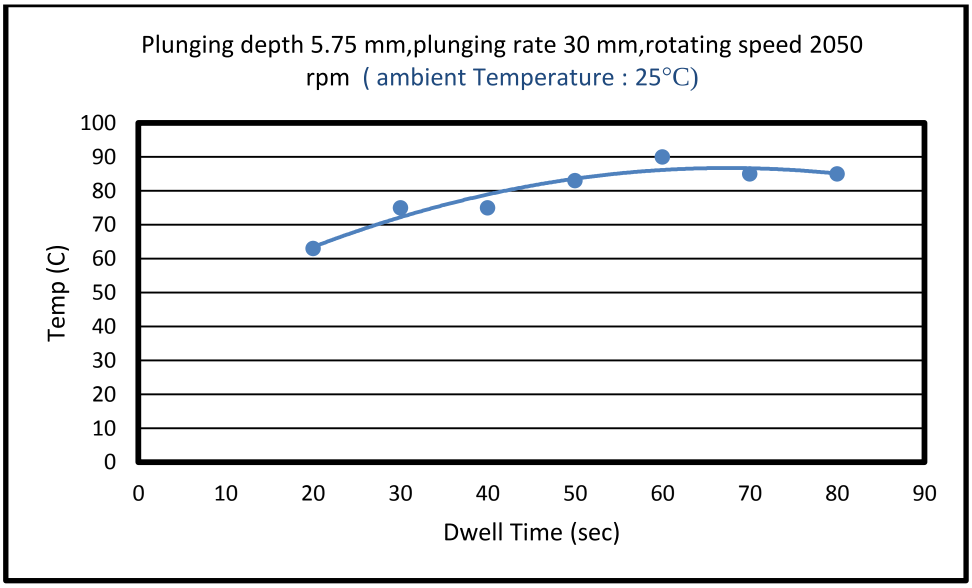


Fig. 12 Effect of dwell time on temperature

It can be seen from Fig. (12) that as the dwell time increases the temperature increases reaching a maximum value of about 90°C at dwell time 60 s and then remains nearly constant. It is worth to mention that the measured temperature in the present study is only the outer temperature of the welded zone. Meanwhile the real temperature may be higher and cannot be measured with the infrared thermometer due to the time delay between the retraction of the tool and the temperature measurement.

Effect of tool rotational speed

It can be noted from Figs. (8-11) that the lap shear force is slightly higher at higher rotating speed 2050 rpm. This may be explained as the rotational speed influences the heat generation due to friction during the welding processes and hence contributes to the joint strength.

Effectiveness of FSSW process

Fig. (13) represents the tensile force as a function of displacement for the base material of tested PE. Same results are recorded during the lap shear test of welded specimens at plunging depth 5.75 mm &dwell time 60 s under speed 2050 rpm, Fig. (14). It can be noticed from these figures that the maximum lap shear force for the welded specimen was 900 N while the maximum tensile force of the base material was 2225N.

A comparison between the strength of the PE sample to that of the attained results for the welded specimen seems to be logic to study the efficiency of the weld procedure.

Referring to Fig. (13) for the base PE material the measured ultimate tensile load is 2225 N, hence the tensile strength will be about 2225/ (25*4) = 22.25 MPa, while for the welded joint, Fig. (14), the measured average diameter of the resulted keyhole after welding is 4.9 mm and the nugget thickness is about 2.3 mm at the weld bond area as shown in Figs. (15a, 15b). As from Fig. (14), the lap shear load is 900 N hence the shear stress to failure will be about 900/ π $[(4.9+4.6)^2 - (4.9)^2]/4$ = 17.29 MPa.

To evaluate the effectiveness of the joining process as well as to compare the joint performances with that produced by other joining solutions, the weld factor f_w is utilized:

$$f_w = \frac{\sigma_{weld}}{\sigma_{base}}$$

Where σ_{weld} and σ_{base} are the strengths of a weld and that of the base material. Therefore, the weld factor achieved from the present results = 17.29/22.25 = 0.777 which agree with previous work [17].

The obtained results would give an indication that for design purposes three welding spots should be used if it is required for the welded joint to sustain the same load as that carried by the PE specimen. (2225/900 = 2.47 practically 3 points) when using welding parameters in the range of adopted values in the present study. However, the number of spots is to be calculated to sustain a specific practical load application.

From Figs. (13, 14) it could be also noticed that for base material the elongation corresponding to a load of 900 N is comparable with that attained at the failure of the welded joint. This can be explaining as the load is increased in the joint while testing, the PE welded specimen start to deform up to a load corresponding to the shear failure load of the joint (900 N) and the deformation stops as the joint fails**.**

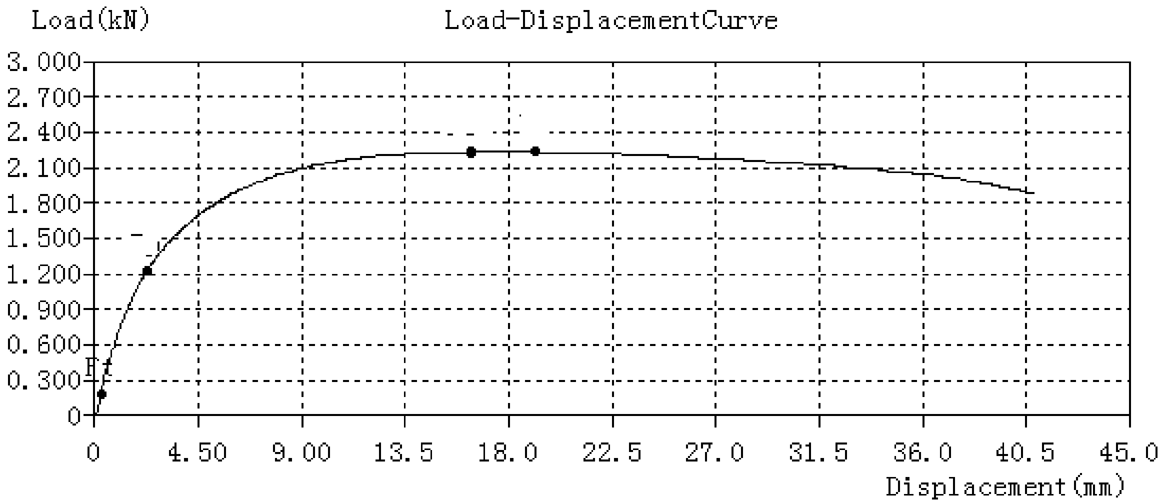


Fig. 13 Load- displacement diagram of base material

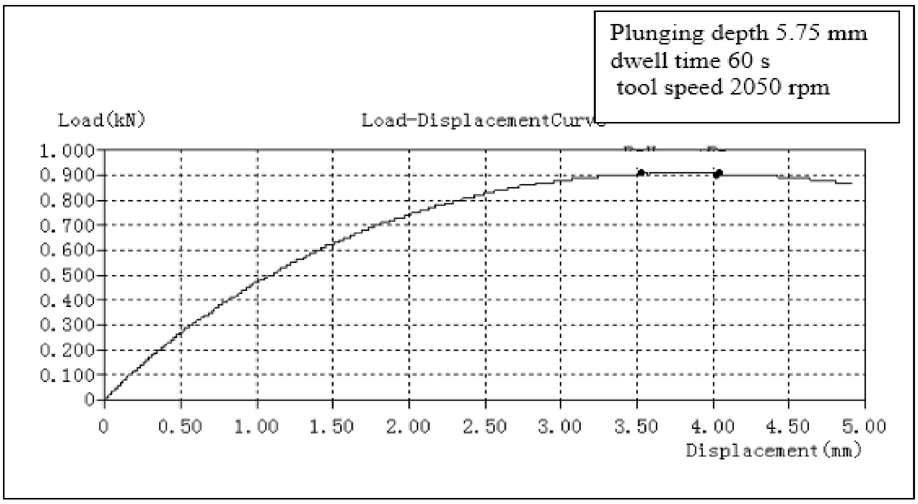


Fig. 14 Load- displacement diagram of lap shear welded specimens

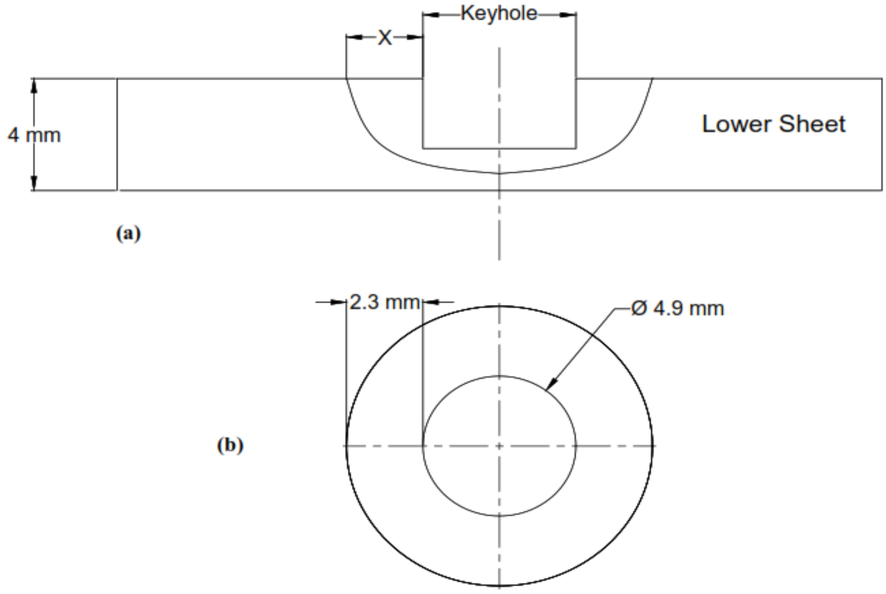
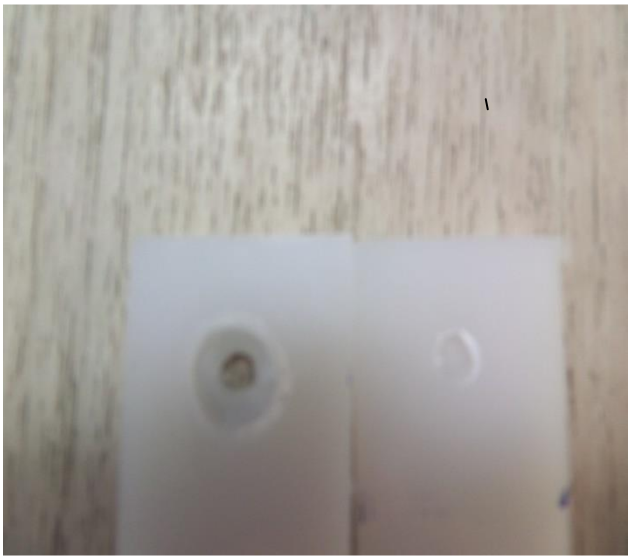


Fig. 15 (a) Schematic illustration of the cross section of FSSW joint and (b) geometry of the weld bonded area, x: nugget thickness

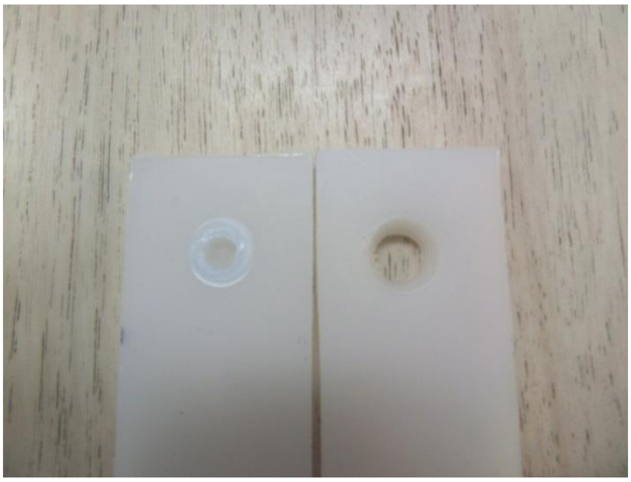
The morphology of the fractured zone of the FSSW specimens

The fractured welded specimens were examined to study the mode of failure after the lap shear test. Figs. (16a, 16b) represent photos for the upper and lower sheets of the fractured specimens.



Upper sheet Lower sheet

Fig. 16 (a) Cross nugget with lap shear force = 240 N
(Tool speed = 2050 rpm, plunging depth = 5.75 mm, plunging rate = 30 mm/min, dwell time = 30 s)



Lower sheet Upper sheet

Fig. 16 (b) Pull out nugget with lap shear force = 900N
(Tool speed = 2050 rpm, plunging depth = 5.7 mm, plunging rate = 30 mm/min, dwell time = 70 s)

Fig. 16 Fractured zone of the FSSW specimens

The welded joint of low value lap shear force fractured with across nugget failure mode with insufficient flow of the joining materials due to low heat generation. Fig. 16 (a). On the other hand, the joint of high lap shear force fractured with a pull-out nugget failure mode and a good welded joint due to a sufficient heat input, Fig. 16 (b). The obtained results confirm the previous work [15]**.**

It is expected that low generated frictional heat results in poor weld, meanwhile precautions may be considered as in polymeric materials that mechanical scission can occur during the FSSW if excessive frictional heat is created in the weld zone [15, 16].

During the FSSW process some polymeric material from the work piece has been ejected from the weld zone outside the weld hole, Fig. (7). this action may be due to the tool rotation and the effect of the inertia forces**.**

It is worth mentioning that the tool material may play a role in the FSSW process [11] as during final stages while withdrawing the tool, some molten polymeric material may adhere to the tool. This has been remarked in the present test. Hence during the process, the plastic material remains attached to the tool surface forming built-up edge, causing a change in the tool geometry and diameter which is undesirable. Thus, the tool should be cleaned before each FSSW process.

Conclusions

1. The experimental results confirm previous findings and hence FSSW technique can be used in industrial welded applications of PE.

2. The FSSW relies on the heat generation; the welding parameters controlling the heat generation are mainly the plunging depth, the dwell time and the tool rotational speed. In the present study, 2050 rpm tool rotational speed, 60 s dwell time and 5.75 mm plunge depth were determined as the optimal welding parameters of PE.

3. FSSW of PE differs than of metals as mechanical scission can occur during the FSSW if too high frictional heat is created in the welded material and then high pressure is applied to it.

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