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Investigation of Weld Forces and Strength of Friction Stir Welded Polypropylene

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Abstract

Friction stir welding (FSW) is an advanced joining technology specifically developed for welding materials that are difficult to weld (e.g. polymers). Over the last two decades, more and more research has been published on the applicability and development of the technique on polymeric materials. The aim of the present study is to investigate the applicability of the method for welding polymeric materials and to analyse the effect of the parameters of FSW. In the tests, 4 mm thick polypropylene sheets were welded by varying two welding parameters (tool speed (n) and feed rate (v_f)) in four levels. Thus, a complete experimental design with 16 measurement points was created. During the welding process, the force components on the tool/workpiece were measured, from which the resultant welding force was calculated and the strength of the joints was characterized by tensile testing. The ratio of the tensile strength of the joints and the tensile strength of the material were used to characterise the process in terms of joint efficiency. During welding, the axial force component (F_z) was the dominant force value. The resultant forces (F_e) decreased with increasing n, while they increased with increasing v_f. The tensile strength of the joint, and hence the bonding efficiency, improved with increasing n, while it deteriorated with increasing v_f. The ratio derived from the ratio of n to v_f was also analysed, with an increase in the ratio showing a decreasing trend in the resulting weld strength and an improving trend in the bonding efficiency.

Keywords

polypropylene, friction stir welding, weld force investigation, joint efficiency

1 Introduction

Friction stir welding (FSW) is a patented mechanical friction welding process [1] developed in the early 1990s for the welding of structural materials with poor weldability, such as aluminium components [2–5]. Its application to polymeric materials was first investigated in 2004 by Nelson et al. [6].

In the last decades, polymeric materials have become a leading material group in several leading industries (e.g. automotive) [7], making the fast, economical and well-automated welding of these materials an important industrial and research topic. Welding processes for polymers include ultrasonic welding [8], laser welding [9] and hot gas welding [10], due to their many advantages (speed, bond strength). Besides conventional techniques, fused filament fabrication (FFF) 3D printing can also be considered as a means of polymer welding [11, 12].

FSW, like the welding processes mentioned above, has a number of advantages, such as low energy consumption, speed of the technology, ease of automation, no filler metal required during the welding process, and no harmful by-products [13, 14].

Other major advantages of the process include the ability to weld thick polymeric materials and the suitability of the welding technology for welding fibre-reinforced thermoplastic polymers [15].

The process uses a rapidly rotating tool with a special design of the shoulder and pin geometry to pass between the parts to be welded in contact. Friction between the pin of the rotating tool and the parts produces the temperature required to fuse the materials, and the rotary motion also ensures that the fused materials are mixed together, thus forming a weld. The tool used in the welding process is recessed into the

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materials to be welded to a depth of penetration approximating to the thickness of the sheets to be welded. Once the weld is completed, the tool is removed from the welding zone. A schematic diagram of a friction stir weld is shown in Fig. 1, together with the weld force components that occur and are measured during the weld [16].

In recent years, there has been a lot of research into FSW. Rezaee Hajideh et al. [17] investigated the effect of four different tool geometries in the FSW of polyethylene (PE) and polypropylene (PP) sheets. The tool geometries tested were threaded cylindrical, plain cylindrical, rectangular cross-section, and triangular cross-section geometries. The tools were made of H13 tool steel and each had a diameter of 10 mm. In their experiments, they used a standing shoulder design with a diameter of 19 mm made of 7075 aluminium alloy. In addition to the pin geometry, the tool speed (n) and feed rate (v_f) were varied in 3–3 stages. Tensile and hardness tests were performed to evaluate the quality of the joint. In all tests, the PE and PP sheets were successfully welded together. A bond tensile strength of 98% was achieved compared to the tensile strength of the PE base material, while the tool with a threaded cylindrical design provided the best quality weld seam at n = 1860 rpm tool speed (n) and v_f = 12.5 mm/min feed rate.

Sahu et al. [18] also investigated the effect of different tool geometries in the FSW of PP. In their study, three different tool geometries of tapered, cylindrical, and rectangular cross sections were analyzed. The tools here were also made of H13 tool steel, however, in this research a tool with a rotating shoulder design was used. Among the welding parameters, the speed of rotation and v_f were varied in 3–3 levels. During the welding process, the force component in the axial direction was measured and the joints were characterized by tensile testing. The force measurements

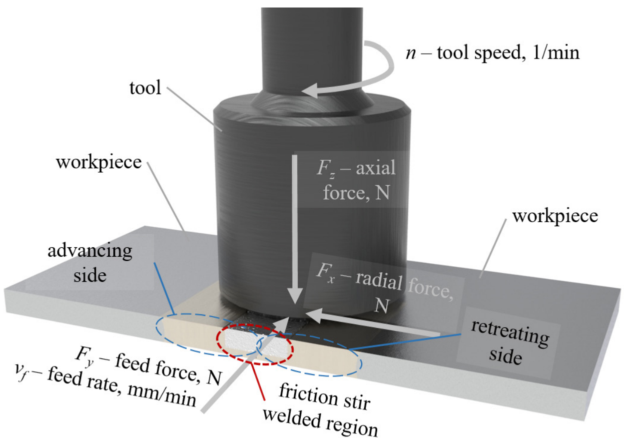

Fig. 1 Schematic of FSW

concluded that the axial direction force decreases with increasing speed, while it increases with increasing v_f. The conical taper pin geometry failed to produce an adequate bond, the latter being the more favourable of the cylindrical and rectangular tool geometries. A aximum bond tensile strength of 19.74 MPa was achieved with the square tap geometry (n = 750 rpm, v_f = 15 mm/min), which is 59.82% of the 33 MPa tensile strength of the base material.

Kordestani et al. [19] also investigated the effect of pin geometry in FSW of PP composite plates. In their studies, they investigated 4 different tool geometries on two types of PP composites (30% glass and 30% carbon fiber). The quality of the joints was characterized by tensile testing and Izod impact testing. Based on the results, the authors concluded that the pin geometry has a strong influence on the aesthetic and mechanical properties of the resulting joint. The tensile strength of the best welds was 30% (glass fibre) and 34% (carbon fibre) of the tensile strength of the base material, while the results of the impact tests showed that the welds had an impact strength of 40% (glass fibre) and 50% (carbon fibre) of the base material.

Nath et al. [20] compared unheated and heated shoulder constructions. In their tests, they measured the torque, feed direction (F_x) and axial direction force components during welding. The workpiece was a 3 mm thick PP sheet, and the v_f was varied in 3 levels during welding. After the welding tests, the morphology and tensile strength of the joints were investigated. It was found that for the unheated shoulder construction, higher forces were generated during welding, while no difference in torque was observed. As the v_f was increased, the force values increased in both directions. When the tensile strength of the joints was tested, the heated shoulder welded joints performed better.

Moochani et al. [21] also conducted a study of FSW of PP sheets using a heated tool with a stationary shoulder design. They justified the compensation of heat loss by the fact that polymers have low thermal conductivity and low coefficient of friction. Their process design incorporated an external variable temperature hot air system and an infrared temperature sensor for accurate tool temperature setting. In comparison with the unheated tool test, it was found that the external heating has a large effect on the tensile strength of the joint, resulting in a bond strength of 96% relative to the strength of the base material.

Rezaee Hajideh et al. [22] investigated the FSW of acrylonitrile butadiene styrene (ABS) and PP sheets. The welds were performed using a heated stationary shouldered tool. The material of the cylindrical tool was H13 tool steel. During the tests, copper powder was placed in pre-punched grooves, to be mixed into the weld joint during the welding process. Among the welding parameters, the speed of rotation, v_f and tool temperature were varied in 3–3 levels. The output parameters were bond tensile strength and hardness. Their test results showed that copper powder resulted in significant improvements in joint tensile strength and hardness.

In a review paper, Hamza and Jalal [23] present research that deals with a particular variant of FSW, FSP. Different reinforcing materials (e.g., graphite, SiO_2) are used in each study to improve the strength characteristics of the joint in this technology. After the review, the authors concluded, that the reinforcing material mixing, heat generation and surface quality are strongly influenced by the speed and v_f.

Eslami et al. [24] carried out a multiaxis force measurement during the FSW of high molecular weight polyethylene (HMW-PE) with a tool with a stationary PTFE shoulder. During the test, 7 measuring points were defined and the v_f, speed, and pin diameter were varied. The authors found that the force measurement system was suitable for measuring the force components during welding and that the v_f and speed had the greatest influence on the radial force (F_x) and feed direction (F_y) forces. The force image was divided into 4 distinct phases and the force variations in each phase were analysed.

Pereira et al. [25] analysed the effect of FSW techniques and parameters on the tensile strength of polymers in a review. They also discussed the importance of tool geometry and shoulder design. Based on the literature reviewed, they evaluated the quality of the weld obtained for each tool geometry and welding parameter. In their study, they discuss several materials, including PP. Based on their results, they conclude that for the applied 4 mm thick PP sheet FSW, the best quality weld joint can be achieved with the threaded cylindrical pin and the stationary heated shoulder.

The aim of the present study is to investigate the applicability of the method for welding polymeric materials and to analyse the effect of the parameters of FSW.

In this paper, the results of FSW tests of 4 mm thick PP sheets presented, detailing the effect of welding parameters on the force components and tensile strength of the welded joints.

2 Materials and methods

The dimensions of the specimens were 90 mm × 85 mm, in order to allow for the fabrication of at least three tensile specimens after welding the two plates together in order to have a sufficient number of test repetitions (Fig. 2).

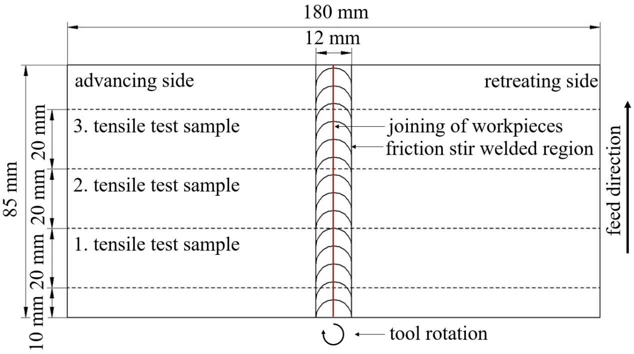

Fig. 2 Cutout layout and numbering of test specimens

Tensile tests were performed with a Zwick Z005 tensile tester at a test speed of 10 mm/min. At each measurement point, three welded joints were tested, and the tensile strength of the base material was also determined from three measurements. The average of the three measurements was 28.8 MPa, which was used in the calculation of joint efficiency. The joint efficiency was determined as follows (Eq. (1)):

$$JE = \frac{\sigma_{\text{max, welded specimen}}}{\sigma_{\text{base material}}} \times 100\%, \quad (1)$$

where $\sigma_{\text{max, welded specimen}}$ (MPa) is the tensile strength of the welded and machined specimens, $\sigma_{\text{base material}}$ (MPa) is the tensile strength of the neat base material.

We also evaluated the welds with non-destructive material tests before the tensile test. Firstly, X-ray CT images were obtained using a YXLON Cheetah FXE-160.51 Multifocus X-Ray CT machine. The tube voltage during the imaging was 70 kV, and the tube current was 22 μA. In addition, stereomicrographs of the welds were taken with an OPTIKA SZM-2 stereomicroscope.

The welding experiments were performed on a Mazak Nexus VCN 410A-II vertical machining centre. The welding tool material used was C45 steel, and a rotating shoulder design was employed. The pin diameter was 12 mm, the shoulder diameter was 29 mm, and the pin geometry was of cylindrical design. The tool is shown in Fig. 3.

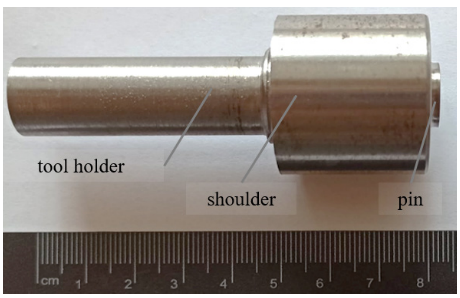

Fig. 3 The tool used for the welding experiments

During the welding processes, the force components (F_x, F_y, F_z in Fig. 1) were measured with a Kistler 9257B piezoelectric force cell mounted under the workpiece gripper. The measuring range of the load cell is $F_x = F_y = -5...5$ kN and $F_z = -5...10$ kN [26].

The three measured force values were used to calculate the resultant force during welding as follows (Eq. (2)):

$$F_e = \sqrt{F_x^2 + F_y^2 + F_z^2}. \tag{2}$$

Among the welding parameters, n and v_f were varied in 4–4 levels. The parameters were determined based on preliminary experiments and literature [18, 22, 27–30]. The welding parameters used are given in Table 1.

During the tests, a complete experimental design was used, so 16 measuring points were determined, which are shown in Table 2, while the location of the measuring points on the speed – feed rate plane is illustrated in Fig. 4.

3 Results

3.1 Investigation of force patterns

The evolution of the force patterns and their effect on the weld is illustrated in Fig. 5 through a top view and X-ray CT image of the weld. The welding process can be divided into three phases based on the force regimes during welding.

After the tool enters the workpiece, the forces generated after reaching a maximum value (Fig. 5, stage I) describe a steady-state phase (Fig. 5, stage II). When the tool exits, the forces decrease to zero (Fig. 5, stage III). These phases, which are distinct in the force-time diagram, can be clearly distinguished in the X-ray CT image of the weld joint and in the top view image of the weld.

Table 1 The welding parameters used

Parameters	Levels			
	1	2	3	4
n (1/min)	500	1000	1500	2000
v_f (mm/min)	50	100	150	200

Table 2 The measurement points and corresponding welding parameters

Measurement point	n (1/min)	v_f (mm/min)	n/v_f
1	500	50	10
2	500	100	5
3	500	150	3.33
4	500	200	2.5
5	1000	50	20
6	1000	100	10
7	1000	150	6.66
8	1000	200	5
9	1500	50	30
10	1500	100	15
11	1500	150	10
12	1500	200	7.5
13	2000	50	40
14	2000	100	20
15	2000	150	13.33
16	2000	200	10

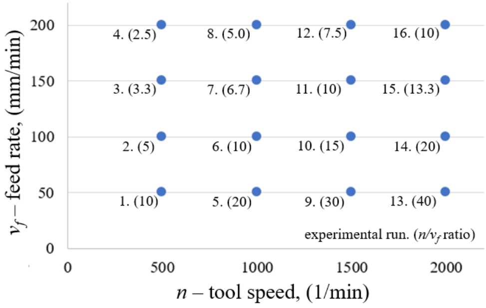

Fig. 4 Positions of the measurement points on the plane of varied parameters (tool rotation, feed rate), the ratio of the parameters is indicated in brackets at each measurement point

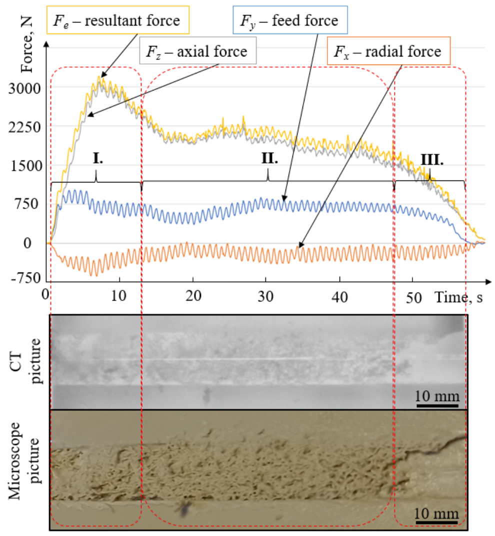

Fig. 5 The forces present during welding and their effect on the welded seam (CT image and top view micrograph of the weld)

3.2 Results of the force analysis

The force analyses were performed by examining the force components shown in Fig. 1 and the resultant force (Eq. (2)). Figs. 6 and 7 show the effect of forces in the F_x and F_y directions as a function of the machining parameters. It can be observed that neither the speed, nor the feed rate, nor the ratio of the speed and feed rate has a significant effect on the two force components over the range of the parameters studied.

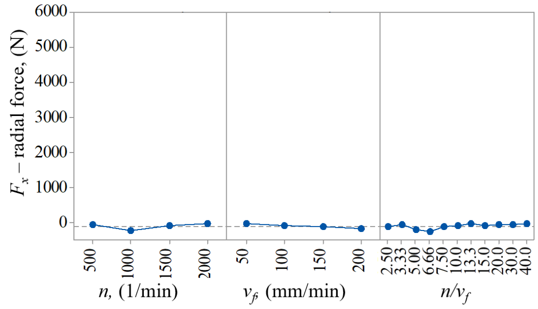

Fig. 6 Effect of welding parameters on the side-directional force component (F_x)

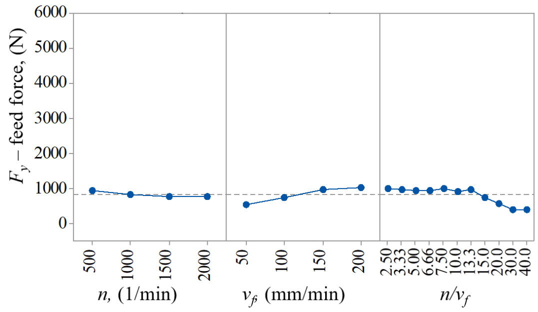

Fig. 7 Effect of welding parameters on the feed-directional force component (F_y)

Fig. 8 shows the variation of axial force F_z as a function of machining parameters. It can be seen that the axial force component is significantly larger than the F_x and F_y components. The value of the force component F_z decreases with increasing speed and increases with increasing feed rate. As for the n/v_f ratio for FSW, the force component F_z shows a decreasing trend with increasing value. Since the value of F_z is significantly higher than the other two force components and is, therefore also the determinant of the resultant force, the resultant force principal action plots (Fig. 9) also show the same trends.

3.3 Joint efficiency

The main effect diagrams of the joint efficiency (Eq. (1)) are presented in Fig. 10. From Fig. 10, it can be observed that while increasing the speed increases the JE, increasing the

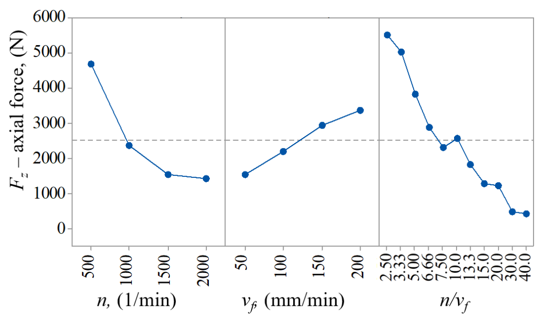

Fig. 8 Effect of welding parameters on the axial force component (F_z)

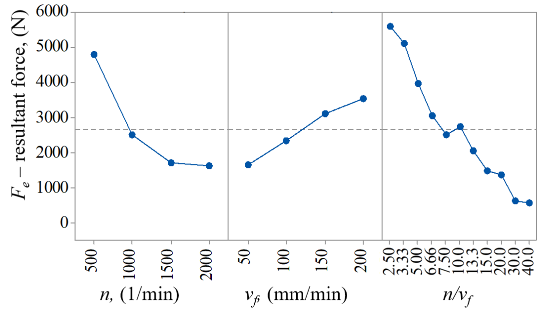

Fig. 9 Effect of welding parameters on the resultant force (F_e)

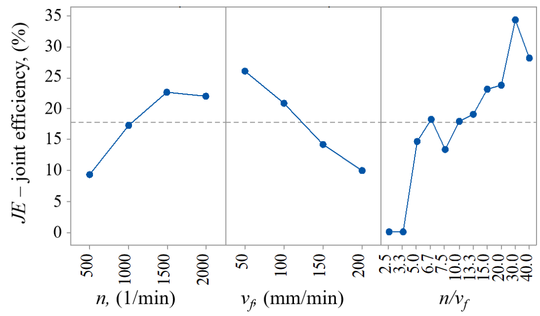

Fig. 10 Effect of weld parameters on the joint efficiency

feed rate decreases it. It can be said that an increase in the n/v_f ratio for friction welding leads to an improvement in the joint efficiency over the parameter range investigated.

4 Conclusions

In the present paper, friction welding tests of 4 mm thick PP sheets were carried out over a wide range of parameters (n = 500 ... 2000 1/min; v_f = 50 ... 200 m/min) at 16 measuring points using a rotary shoulder tool. The experiments were evaluated by analysing the effect of the welding parameters on the force components during friction welding, and the bonding efficiency was determined from the results of the tensile test of specimens made from the welded pieces. Based on our investigations, the following conclusions can be drawn:

- Among the force components present during welding, the axial force component (F_z) is the dominant one.
- As the tool speed increases, the axial (F_z) and hence the resultant forces (F_e) during welding decrease, while the axial component (F_z) increases with increasing feed rate.
- While the ratio n/v_f increases with increasing speed and feed rate, the axial force F_z and the resultant force F_e show a decreasing trend.
- From the evolution of the force plots, one can infer the quality of the weld as well as its aesthetic appearance. A sudden change in the force pattern may indicate a weld defect.

- In the parameter range investigated, the JE increased with increasing speed, while it decreased with increasing feed rate. The best bonding efficiency and the lowest resultant force are found at high n/v_f.
- In the tests, the best joint efficiency was obtained at n = 1500 1/min speed and v_f = 50 mm/min feed rate, at which the joint efficiency was 34% (9.91 MPa).

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