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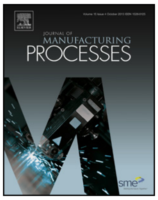

Influences of friction stir welding parameters on morphology and tensile strength of high density polyethylene lap joints produced by double-pin tool

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ABSTRACT

A double-pin tool is adopted in the submerged friction stir lap welding of high density polyethylene sheets in the present investigation. Effects of welding parameters (rotational speed, welding speed, plunge depth) on weld morphology and tensile strength are investigated. The experiment is arranged by taguchi's L9 orthogonal array. Macromorphology and microstructure of three typical welds are observed and compared. Analysis of variance is adopted to assess the importance of each welding parameter to the joint strength. The results show that joint with low tensile strength presents poor weld formation. Voids and cracks can be observed in the nugget by scanning electron microscope. Joint with high strength shows excellent nugget formation and inverted bowl-shaped weld cross section. Joint strength increases with the increase of rotational speed or the decrease of welding speed. Small or large plunge depth is not beneficial to the joint strength. The joint with maximum tensile strength of 15.3 MPa is obtained at rotational speed of 1300 r/min, welding speed of 20 mm/min and plunge depth of 0.1 mm. Welding speed has the most significant effect on the joint strength, about 75.37%, while plunge depth has the least influence.

1. Introduction

Friction stir welding (FSW) technology was invented and experimentally proven at The Welding Institute (TWI) in England in 1991 [1]. It has been demonstrated to be feasible in welding many metals and alloys and the strengths of the welds are usually high [2–5]. Nowadays, with the promotion of toughness and strength-to-weight ratios of thermoplastics and their composites, some metal components are gradually being substituted by thermoplastic components in some fields, especially in automotive industry [6]. The increased application of thermoplastics in automobiles can effectively reduce the weight of vehicles, which in turn reduces the energy consumption and improves their performance [6]. Common welding methods to connect thermoplastics can be divided into three categories according to heat generation, including thermal welding (i.e. Laser welding [7] and hot-tool welding [8]), electromagnetic welding (i.e. Induction welding [9]) and friction welding (i.e. Vibration welding [10], ultrasonic welding [11] and friction stir welding [12–20]). FSW of thermoplastics has been demonstrated to be advantageous by strand [12], who compared it with other welding methods in several aspects. Soon afterwards, much excellent work has been done. Wherein, the optimization of tools and the change of welding media have been proved to be effective ways to improve weld formation and promote joint strength.

Hot "shoe" was developed by Strand [13] in the FSW of polypropylene (PP) plates. It was able to provide additional heat to the weld zone through the internal heater and trap the displaced materials. Meanwhile, it applied pressure to the weld seam in the welding process. Mendes et al. [14] removed the heater from the stationary "shoe" in the FSW of Acrylonitrile-Butadiene-Styrene (ABS) sheets and successfully obtained a weld with smooth crown appearance and defect-free retreating side. Axial force had slight effect on the joint strength but it had important influence on the plastic strain performance of the weld. Vijendra et al. [15] friction stir welded high density polyethylene (HDPE) sheets with an induction heated tool and found that joint with maximum strength can be produced at tool temperature of 45 °C and rotational speed of 2000 rpm. "Self-reacting tool", which was designed with two shoulders that touched the upper and beneath surface of the workpiece respectively, was utilized by Pirizadeh et al. [16] to remove the root defect of ABS joints. Rezgui et al. [17] designed a tool with scraper system to prevent heat loss as well as modify temperature

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Table 1
The physical properties of HDPE.

Properties	Melting point (°C)	Tensile strength (MPa)	Elongation at break (%)
Data	130–137	23	550

distribution along the weld zone. Payganeh et al. [18] studied four tools with different pin geometries in the FSW of PP composite. They found that the tapered pin with groove was the most suitable tool to produce weld with smooth appearance and high tensile strength. Eslami et al. [19] reported that the stationary shoulder that made of Teflon was the best to produce weld with excellent surface quality and grooved pin can properly promote material flow. Gao et al. [20] developed submerged friction stir welding (SFSW) technology to weld HDPE sheets and compared the joint strength with the joints produced in air condition. They drew a conclusion that SFSW technology was better in producing joints with higher strength.

Until now, the tool investigated in the FSW of thermoplastics were mainly consist of a single pin. A FSW tool with more than one pins has not been investigated before. However, the increase of pins may facilitate heat input and material flow in the welding process and then improve the weld formation and joint quality. Therefore, in the present paper, a tool with double pins was fabricated and applied in the friction stir lap welding (FSLW) of HDPE sheets. Also, the welding operation was designed to be carried out underwater due to its advantage demonstrated by Gao et al. [20] in the previous research. The feasibility of FSLW of HDPE sheets underwater by double-pin was demonstrated first and then the effect of welding parameters (rotational speed, welding speed and plunge depth) on the weld formation and joint strength was investigated.

2. Materials and methods

The commercial HDPE sheets with the size of $200 \times 200 \times 4\,\text{mm}^3$ are welded in the experimentation. The partial physical properties of HDPE are shown in Table 1. To clearly observe the shape of weld joints, white and black sheets are adopted. They are clamped on the working table by properly designed clamping system in lapped configuration. The newly designed tool with two symmetric pins is shown in Fig. 1. Fig. 1a and b presents the size and the photograph of the tool, respectively. It was reported that the loss of melted material from the weld zone was the cause to the phenomenon of discontinuity on the retreating side [21]. Therefore, the shoulder bottom is designed with concave configuration to prevent material extrusion. At the same time, SFSW technology is adopted in the present experiment. On the one hand, compact touch between the shoulder bottom and sheet surface can be ensured during the welding process because material underlying the shoulder is hard to be softened and then be expelled outside by rotating shoulder. On the other hand, water can accelerate the solidification rate of the nugget material, avoiding heat concentration in the nugget zone and reducing the temperature gradient [20]. However, heat transmission rate from the under-shoulder stirring zone to surrounding water should be restricted during the welding process because sufficient heat is necessary to the softening and the mixture of nugget material. Therefore, 201 stainless steel with low thermal conductivity is selected to fabricate double-pin tool. To carry out the experiment under water, a water tank with the size of $160 \times 160 \times 12\,\text{mm}^3$ is installed on the surface of the lapped upper HDPE sheet. The above-described welding process is called submerged friction stir lap welding (SFSLW). Fig. 2a and b shows the top view and the sectional view of SFSLW of HDPE by double-pin tool, respectively.

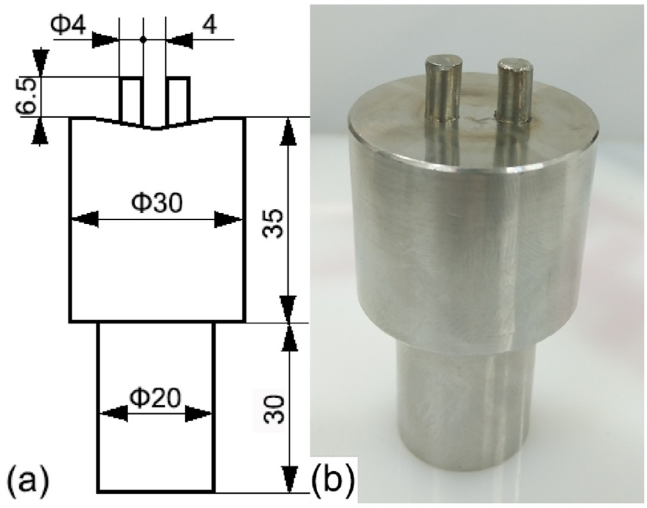

Fig. 1. (a) The size and (b) the photograph of double-pin tool.

Table 2
Three levels and the corresponding values of each FSW parameter.

Symbol	Welding parameters	Level 1	Level 2	Level 3
N	Rotational speed (r/min)	700	1000	1300
V	Welding speed (mm/min)	20	30	40
D	Plunge depth (mm)	0	0.1	0.2

In this experimentation, the effect of rotational speed, welding speed and plunge depth on the weld strength and morphology is investigated. Table 2 shows the symbols, levels as well as the corresponding values of each welding parameter. According to Table 2, the welds performed in different levels of welding parameters can be simplified and designated as below: letter N followed by the level of rotational speed, letter V followed by the level of welding speed and letter D followed by the level of plunge depth. Therefore, N2V1D2 represents the weld performed in rotational speed of 1000 r/min, welding speed of 20 mm/min and plunge depth of 0.1 mm. Taguchi's L9 orthogonal array is used to design the experiment [22] and the specific experimental arrangement is shown in Table 3. According to the parameter combinations, the welds are produced using a modified Computer Numerical Control (CNC) milling machine. The weld width variations along weld thicknesses on both advancing side and retreating side are measured, as the schematic shown in Fig. 3. W_{2A} means the varied weld width in the weld thickness of 2 mm on the advancing side, W_{4R} means the varied weld width in the weld thickness of 4 mm on the retreating side, and so forth. The varied weld widths are listed in Table 4 and each result is obtained by averaging the measured W_{2A}, W_{2R}, W_{4A} and W_{4R} of six cross sections of three specimens cut from one weld according to Fig. 4. The size of the tensile test specimens are shown in Fig. 5, which is determined according to GB/T 11997 standard. Tensile tests are carried out at room temperature through the SANS

Table 3
Experimental arrangement by L9 orthogonal array.

Experiment number	FSW parameters			Error
	N (r/min)	V (mm/min)	D (mm)	
1	700	20	0	
2	700	30	0.1	
3	700	40	0.2	
4	1000	20	0.1	
5	1000	30	0.2	
6	1000	40	0	
7	1300	20	0.2	
8	1300	30	0	
9	1300	40	0.1	