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Technical Report

The optimization of friction stir welding process parameters to achieve maximum tensile strength in polyethylene sheets

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ABSTRACT

The weld strength of thermoplastics, such as high density polyethylene and polyprophylene sheets are influenced by friction stir welding parameters. The determination of the welding parameters plays an important role for the weld strength. For the influential use of the thermoplastics joints, the weld should have adequate strength. The quality of the joint was evaluated by examining the characteristics of the joint efficiency as a result of ultimate tensile strength. In this study, the Taguchi approach of parameter design was used as a statistical design of experiment technique to set the optimal welding parameters. The experiments were arranged by using Taguchi's L9 orthogonal array. The signal-to-noise ratio and the analysis of variance were utilized to obtain the influence of the friction stir welding parameters on the weld strength. Finally, the results were confirmed by further experiments.

1. Introduction

Modern thermoplastic materials are used in an expanding range of engineering applications, such as in the automotive industry, due to their enhanced stress-to-weight ratios and toughness. Even though plastics offer a high degree of design freedom and processing ability, the fabrication of larger and complex parts usually requires joining technologies [1], such as friction stir welding. Friction stir welding (FSW) is a rapidly maturing solid state joining process that appears as a promisingly ecologic weld method that enables to diminish material waste and to avoid radiation and harmful gas emissions usually associated with the fusion welding techniques [2,3]. The main process parameters affecting material flow and weld quality contain the tool rotation speed, tool traverse speed, the vertical pressure on the tool, the tilt angle of the tool and the tool geometry [4,5]. During processing, a nonconsumable tool attached with a specially designed pin was inserted to the butting edges of the plates to be joined. The tool shoulder had to touch the plate surface. Under this condition the tool was rotated and traversed along the bond line. Thus, frictional heat was generated. The tool rotation and traverse expedite material flow from the front to the back of the pin and welded joint were produced. The process was suitable for joining the plates and sheets; however, it can be employed for pipes and the hollow sections and positional welding [6]. FSW aims for structural demanding applications to provide high-performance benefits in industry [7].

Although the FSW process was initially developed for Al-alloys [8–10], it also has a great potential for the welding of copper [11], titanium [12], steel [13], magnesium [14], metal matrix composites [15], and different material combinations [16]. Recently, some researchers have studied the application of FSW and FSSW to thermoplastics [17–19].

In order to investigate the efficiency of FSW process parameters, most researchers follow the conventional experimental procedures, i.e. varying one parameter at a time while keeping the other parameters constant. This conventional parametric design of the experimental approach is time consuming and requires excessive resources [20]. In order to solve this problem, there are different methods of achieving the desired output variables by developing new models. The Taguchi method is one of the techniques that could be applied to optimize the welding parameters [21]. The Taguchi method has been found to be a simple and robust technique for optimizing the welding parameters [19]. This method is widely used to optimize process parameter values in order to improve the quality properties of a product. Conventional experimental design methods are generally complex and not always reach the desired objectives. Moreover, this method provides advantages over the conventional experimental design methods; it reduces economically the variability of the response variable, shows the best way to find out the optimum process conditions during experimental studies, it is an important tool for improving the productivity and it can be applied to any process [22]. It appears that very few studies on the optimization of FSW process parameters of polyethylene sheets using Taguchi method has been reported as known by the author [23]. Considering the above fact, the aim of this research was to analyze the effect of each processing parameter (i.e. tool

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Table 1
FSW process parameters and levels.

Symbol	Welding parameter	Unit	Level 1	Level 2	Level 3
A	Tool rotation speed	(rpm)	1500	2100	3000
B	Tool traverse speed	(mm/min)	45	75	115
C	Tilt angle	(°)	1	2	3

rotation speed, tool traverse speed and tilt angle) by the Taguchi L9 method on the optimum tensile strength of FSWed joints of the polyethylene sheets.

2. Experimental procedure

In this study, three-level process parameters; tool rotation speed, tool traverse speed and tilt angle were analyzed as shown in Table 1. Trial experiments were carried out according to the principles of the design of the experiments in order to determine the effect of the main process parameters. An L9 orthogonal array with four columns and nine rows was applied. The experimental layout for the three welding parameters using the L9 orthogonal array is shown in Table 2. Since the L9 orthogonal array has four columns, each welding parameter is assigned to a column, and the last column is left empty for the error in the experimental studies. The orthogonality is not lost by letting one column of the array empty [19].

The experimental studies were performed using commercial $50 \times 130 \times 4\ \text{mm}^3$ dimension high density polyethylene (HDPE) sheets to fix the operating range of FSW process parameters. The tensile strength of the base HDPE was 22.5 MPa. The HDPE sheets were placed on the backing plate to avoid separation during the FSW process. FSW process of the HDPE sheets is shown in Fig. 1. They were single pass friction stir butt welded using an FSW adapted milling machine. The temperature variations in the joint line were measured during the welding process by an infrared thermometer device which is capable of measuring −50–550 °C. The FSW tool, with a 18 mm diameter shoulder and a pin with a diameter of 6 mm, a length of 3.8 mm was made from SAE 1050 steel heat treated to a hardness of 40 HRC. The pin was plunged into the HDPE sheets at the joint line up to the shoulder touching the surface of the HDPE sheets. While the rotating tool advanced, the temperature of the HDPE sheets below the tool shoulder increased and the strength of the HDPE decreased. Hence, the tool moved on the joint line. Since, the tool going through the joining zone cooled down, the two HDPE sheets joined. The joint efficiency was evaluated by means of the ultimate tensile tests (UTS). The tensile tests were carried out according to EN ISO 527 [24] by a universal type tensile test machine as shown in Fig. 2. At least three specimens were tested under the same conditions to guarantee the reliability of the tensile test results.

3. Results and discussion

3.1. Signal to noise ratio (S/N ratio)

The Taguchi method uses the signal to noise (S/N) ratio in replace of the mean value to convert the experimental result data into a value for the evaluation characteristic in the optimum setting analysis [25]. Some measurable responses to the analysis output during the operation of any engineering system or process are called performance characteristics [26]. Tensile strength is the main characteristic recognized in this study defining the quality of FSW joints of HDPE sheets. In order to evaluate the influence of the welding parameters on the response, the means and S/N for each welding parameter were calculated. The S/N ratio of the

Table 2
Experimental layout using an L9 orthogonal array.

Experiment number	FSW process parameters			Error
	A	B	C	D
	Tool rotation speed (rpm)	Tool traverse speed (mm/min)	Tilt angle (°)	
1	1500	45	1	
2	1500	75	2	
3	1500	115	3	
4	2100	45	2	
5	2100	75	3	
6	2100	115	1	
7	3000	45	3	
8	3000	75	1	
9	3000	115	2	

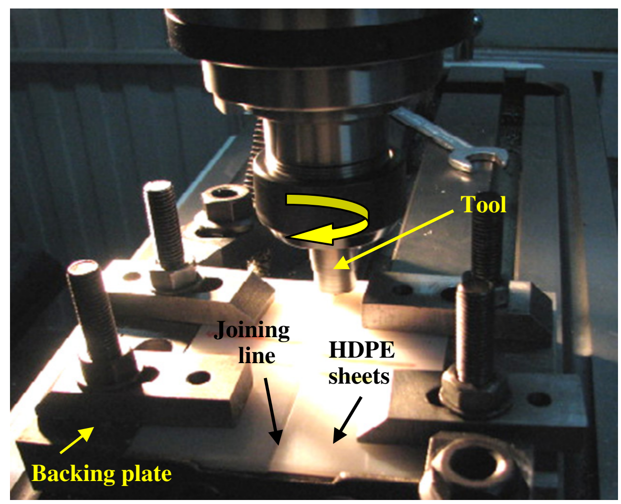

Fig. 1. FSW process of the HDPE sheets.

Fig. 2. Tensile test operation of the HDPE sheets joined by FSW.

weld strength was analyzed according to the principles of "the larger – the better" characteristic which can be explained as follows [20,27].

$$\eta = -10\log = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{T_i^2} \tag{1}$$