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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 $50 \times 130 \times 4\ mm^3$ 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	

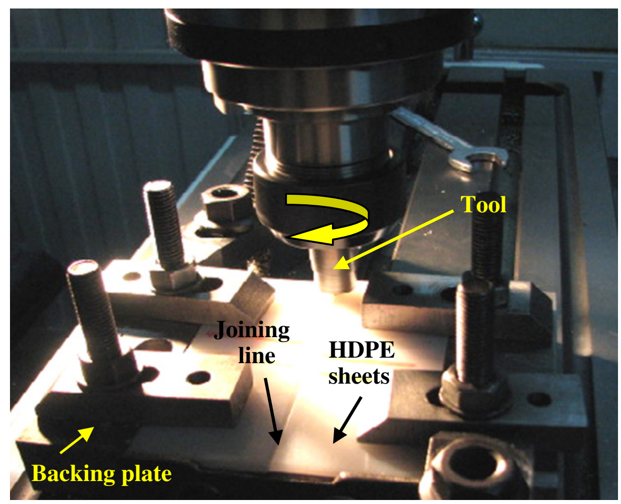

Fig. 1. FSW process of the HDPE sheets.

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].

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

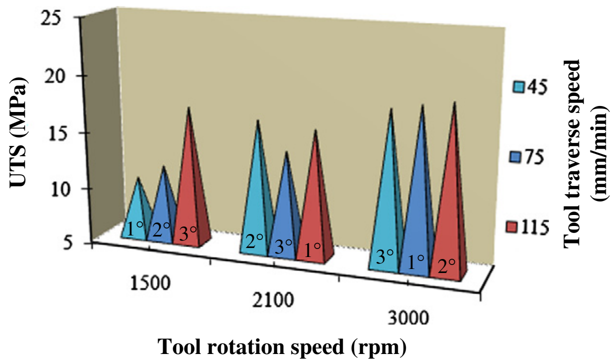

Fig. 3. Effect of welding parameters on tensile strength of the HDPE sheets joined by FSW.

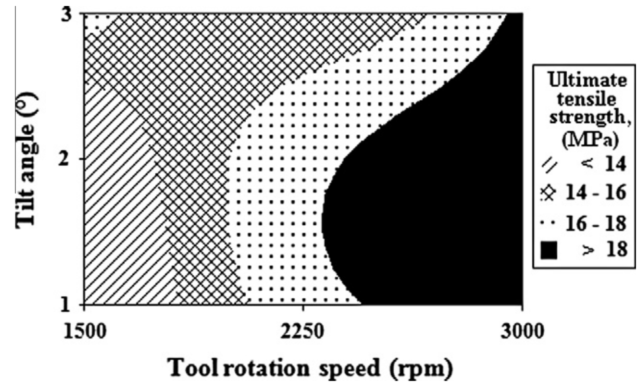

Fig. 4. ANOVA analyses for optimum tool rotation speed and tilt angle on ultimate tensile strength.

Table 3
Tensile test results and calculated S/N ratios.

Experiment number	Ultimate tensile strength (MPa)	Joint efficiency (%)	Calculated S/N ratio (dB)
1	10.4	46.2	20.34
2	11.7	52	21.36
3	17.2	78.2	24.71
4	16.6	73.8	24.40
5	14.1	62.7	22.98
6	16.2	72	24.19
7	18.5	82.2	25.34
8	19.0	84.4	25.57
9	19.4	86.2	25.75

where n is the number of the tests and T_i is the experimental value of the ith quality characteristics [20]. The response of the S/N ratio (η) for each level of the welding parameters was acquired by using MINITAB statistical software. The effect of the friction stir welding parameters on the tensile test results for the design of the experiments are shown in Fig. 3. As shown in Table 3, these tensile test results and the corresponding S/N ratio were calculated with Eq. (1).

During the welding process, the temperature measurements were registered by different welding parameters tool rotation speed 1500–3000 rpm and tool traverse speed 45–115 mm/min. show the range of the reached temperature variations between 120 and 165 °C. The melting temperature of HDPE is about 132 °C [19]. This proves that the welding of HDPE is produced in a liquid state by melting the material [28]. If the amount of the heat generated is sufficient, the produced joint can diffuse to the root of the weld. In most of the welded samples the decrease of the tensile strength is owing to the lack of diffusion and root defects. As the shoulder can have an important effect on material behaviors on the upper surface of the weld, this effect is highly reduced when the material gets closer to the bottom surface of the welding sheets [23].

As shown in Fig. 3 and Table 3, the tensile test results exhibited that the friction stir welded of HDPE sheets with a tool rotation speed 3000 rpm, tool traverse speed 115 mm/min. and tilt angle of 2° obtained the maximum tensile properties. The maximum tensile joint efficiency value was obtained about 86.2% ($UTS_{FSW}/UTS_{Base\ material} \times 100$). In this welding parameter no void or crack formation was observed in the joining zone. The lowest tensile joint efficiency value of 10.4 was 46.2% of the base HDPE sheets.

As the experimental design was orthogonal, it was possible to divide each welding parameter into three levels. For instance, the mean S/N ratio for tool rotation speed at levels 1, 2 and 3 can be computed with mean S/N ratios for the trials 1–3, 4–6 and 7–9, respectively [19]. These results are exhibited in the initial line of the Table 4. Table 4 shows the mean S/N response table for each level of the welding parameters. The total mean S/N ratio of the nine experiments was calculated as 23.85 dB.

3.2. Analysis of variance

A better impression for the relative effect of the different welding parameters on the tensile test was acquired by the decomposition of variance, which is called analysis of variance (ANOVA) [29]. The purpose of ANOVA is to determine which welding parameters highly affect the quality feature statistically [27,30]. According to the results that are shown in Table 3, the graphs show the influence of the welding parameters on the tensile strength of HDPE sheets joined by FSW. The graphs are shown in Figs. 4–6. All of the black zones in the graphs show the maximum ultimate tensile strength. Fig. 4 shows ANOVA analyses for the optimum tool rotation speed and tilt angle on the ultimate tensile strength. For the relation between the tool rotation speed and tilt angle the maximum UTS was confirmed by welding parameters of 3000 rpm and 2° as shown in Fig. 4. The relation between tool rotation speed, tool traverse speed and tilt angle in Figs. 5 and 6 similar trends were observed as shown in Fig. 4.

Fig. 7 shows the main effects plot for mean and the S/N ratios. In this figure, the value of the total mean of the S/N ratios is shown by the dashed-line [27]. In this figure, the level effects of each welding parameter is shown. For instance, the mean S/N ratio is increased from C_1 to C_3. It means that the joining efficiency increases with the increase of the tilt angle. The tool rotation speed and tool traverse speed has a negative effect according to the tilt angle.

Table 4
The mean S/N response table for tensile strength.

Symbol	Welding parameters	Mean S/N ration (dB)				Effectiveness rank
		Level 1	Level 2	Level 3	Max–min	
A	Tool rotation speed (rpm)	22.14	23.86	25.56	3.42	1
B	Tool traverse speed (mm/min)	23.31	23.36	24.89	1.58	2
C	Tilt angle (°)	23.37	23.84	24.35	0.98	3

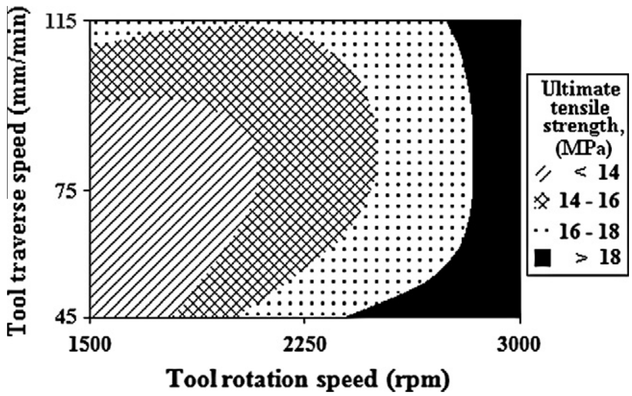

Fig. 5. ANOVA analyses for optimum tool rotation speed and tool traverse speed on ultimate tensile strength.

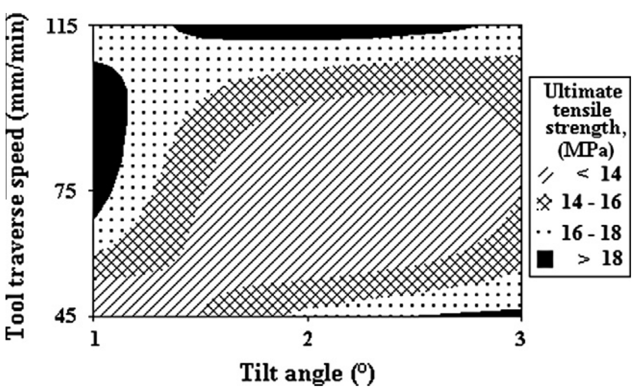

Fig. 6. ANOVA analyses for optimum tilt angle and tool traverse speed.

The results of ANOVA for tensile strength of means were calculated and are shown in Table 5. Statistically, The *F*-test was performed to study the importance of the welding parameters. Larger *F* value displays that the variation of the welding parameters produces a big change on the effectiveness [29]. The results of ANOVA reveal that the evaluated welding parameters are significant factors affecting the tensile strength of FSW joints [20].

3.3. Interpretation of the experimental results

3.3.1. Rate of contribution

The rate of contribution is the part of the total range recognized in the experiment associated to each important welding parameter. The rate of the contribution is a function of the sum of the squares for each important item; it expresses the relative force of a welding parameter to reduce the range. If the welding parameter levels are carried out precisely, the total range can be minimized by the quantity of indicated with the rate of contribution [20].

In this study, for the HDPE sheets the tool rotation speed was a highly important factor and played an extreme role in impressing the ultimate tensile strength and for the joint efficiency of the welding. The effect of each control factor upon the welding process can be observed in Table 5. Only 5.456% of the variance was induced by experimental errors. It proves that the experimental design was very successful. The rate of the contribution of the tool rotation speed, tool traverse speed and tilt angle is shown in Fig. 8, where the rate of the contribution for the welding parameters can be seen. The most important factor that influences the FSW process was the tool rotation speed with 73.85% contribution rate. The total contribution rate of the FSW parameters was 99.9%.

3.3.2. Prediction of the optimum tensile strength

The relation between the experimental investigations and quantitative predictions for the tensile tests of HDPE sheets joined by FSW reveals the mechanical properties depending on the welding parameters [28]. The prediction of S/N ratio ($\hat{\eta}$) and the quality characteristic for the optimum level of the design parameters can be calculated as stated below [31]:

$$\hat{\eta} = \eta_m + \sum_{i=0}^{o} (\bar{\eta}_i - \eta_m) \tag{2}$$

where (η_m) is the total mean S/N ratio, ($\bar{\eta}_i$) is the mean S/N ratio at the optimum level, and o is the number of the main design parameters that affects the quality affection.

According to the main effects plot for S/N ratios as shown in Fig. 7, the optimum welding parameters for joining efficiency were set down as tool rotation speed at level 3, tool traverse speed at level 3 and tilt angle at level 3, i.e. A3B3C3 from S/N and ANOVA analysis. Similar results were reported as A1B3C2 by Bilici et al. who studied the optimization of the welding parameters for friction stir spot welding of HDPE sheets using taguchi method [19].

3.3.3. Confirmation test

After the optimum level of the welding parameters was determined, the final step was verifying the improvement of the UTS using the optimum level of the welding parameters. The initial parameters were determined as A1B1C1 from Fig. 7. The tool rotation speed, tool traverse speed and tilt angle were set at 3000 rpm, 115 mm/min, and 3°, respectively. The comparison of the predicted and experimental UTS of these parameters are shown in Table 6. Three confirmation tests were performed to the UTS and the average value of HDPE sheets joined by FSW was 21.35 MPa. The confirmation test showed that the UTS and joint efficiency improved approximately 112% and 105% respectively from initial welding parameters.

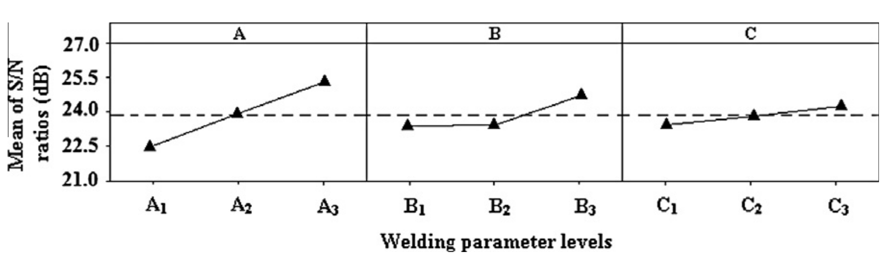

Fig. 7. The main effect plot for S/N ratios.

Table 5
Results of the ANOVA for tensile strength.

Symbol	Welding parameters	Degrees of freedom	Sum of squares	Mean square	F	Contribution (%)
A	Tool rotation speed (rpm)	2	17.543	8.771	3.22	73.85
B	Tool traverse speed (mm/min)	2	4.814	2.407	0.88	20.18
C	Tilt angle (°)	2	1.434	0.717	0.26	5.96
Error		2	5.456	2.728		0.01
Total		8	29.247			100

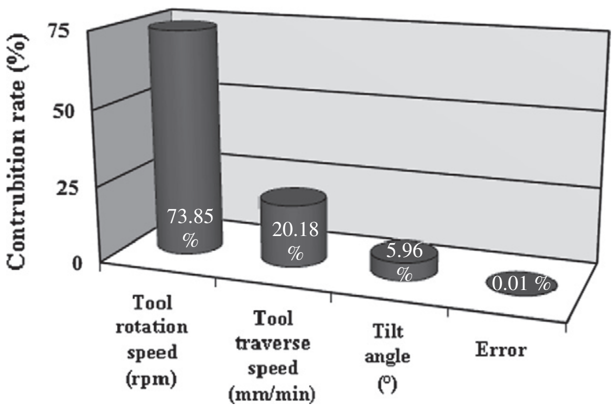

Fig. 8. Rate of the contribution for welding parameters.

Table 6
Results of the confirmation test.

	Initial welding (Experimental)	Optimum welding parameters	
		Prediction	Experimental
Parameter levels	A1B1C1	A3B3C3	A3B3C3
Ultimate tensile strength (MPa)	10.04	21.04	21.55
Calculated S/N ratio (dB)	20.34	27.08	27.79

4. Conclusions

In this investigation the applicability of the friction stir welding on HDPE sheet was studied by using the Taguchi method. The following conclusions can be drawn based on the experimental and analytic results.

(1) The L9 Taguchi orthogonal designed experiments of FSW on HDPE sheets were successfully conducted.
(2) The tool rotation speed plays an important role and contributes 73.85% to the overall welding parameters. The tilt angle was found to be the least contribution welding parameter.
(3) The optimum welding parameters for the UTS are the tool rotation speed of 3000 rpm, the tool traverse speed of 115 mm/min and the tilt angle of 3°.
(4) The confirmation test shows that the UTS and joint efficiency improved approximately 112% and 105% respectively from initial welding parameters.

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