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Optimization of process parameters for friction stir lap welding of carbon fibre reinforced thermoplastic composites by Taguchi method†

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Abstract

Friction stir welding process parameters such as welding speed, rotational speed and tilt angle affect the strength of the weld joint. For maximizing the weld strength, these process parameters must therefore be properly selected and optimized. This study presents an application of Taguchi method to optimize process parameters like welding speed, rotational speed and tilt angle to maximize lap weld tensile-shear strength in 4 mm thick polypropylene composite sheets with 20 wt% carbon fiber. To this end, a L9 orthogonal array of Taguchi method using three factors at three levels was used. Analysis of variance and confirmation tests were conducted. The results indicated that welding speed, rotational speed and tilt angle are respectively the significant parameters affecting the lap weld strength. Optimization results also showed that tensile-shear strength of 6.06 MPa was obtained when welding speed, rotational speed and tilt angle were 25 mm/min, 1250 rpm and 1 degree, respectively.

Keywords: Friction stir welding; Polypropylene composite; Taguchi method; Tensile-shear strength

1. Introduction

Friction stir welding (FSW) is a relatively new welding process developed and patented by the welding institute (TWI) in England in 1991. It is based on frictional heat generated between a rotating tool and the two parts to be welded. Unlike the traditional welding processes, this technique does not heat the material to its melting point. It welds the material in its softened semi-solid state [1]. This is useful for applications where it is important to keep the original characteristics of the material. The main FSW parameters affecting material flow, heat input and weld quality are welding speed, tool rotational speed, tilt angle, axial force and tool geometry [2-4].

Although the FSW process was initially developed for Al-alloys [5-8], it also has a great potential for welding of magnesium, titanium, steel, metal matrix composite, and different material combinations [9-14]. Recently, some researchers have studied the application of FSW and friction stir spot welding (FSSW) for polymers and polymer composites [15-17].

The survey of the previous works shows that FSW has been mostly used for welding of metals and polymers. Therefore, it deserves to investigate the ability of this process for welding of polypropylene (PP) composites reinforced with carbon fiber (CF). Although research on friction stir butt welding of PP composites has been carried out [17], but lap welding of PP composite with 20 wt% CF by FSW has not been reported yet. This study is therefore intended to investigate the effects of FSW parameters on lap shear strength of PP composite welds with 20 wt% CF.

The Taguchi experimental design method which uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments offers advantages over the classical experimental design methods which become too complex and difficult to use specially when the number of parameters to be studied increases [18-23]. The Taguchi design method has been found to be a simple and robust technique for optimizing the welding parameters [24, 25]. Considering the above fact, the aim of this research is to analyze the effect of welding speed (WS), rotational speed (RS), and tilt angle (TA) on weld tensile-shear strength (TSS) of friction stir welded joints of the PP composites with 20 wt% CF sheets using the Taguchi L9 method.

2. Experimental procedures

2.1 FSW process parameters

The FSW process parameters that may influence the quality of FSW joints are WS, RS, and TA [4]. In present investigation, three levels of these process parameters were considered after conducting trial runs. The experimental ranges for pa-

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Table 1. FSW process parameters and their levels.

Symbol	Welding parameter	Unit	Level 1	Level 2	Level 3
RS	Rotational speed	rpm	800	1000	1250
WS	Welding speed	mm/min	16	20	25
TA	Tilt angle	degree	0	1	2

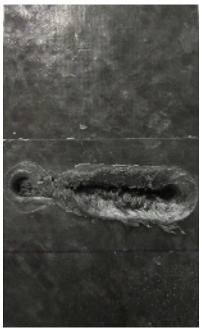

Fig. 1. Weld joint obtained at RS = 630 rpm, WS = 12 mm/min and TA = 0°.

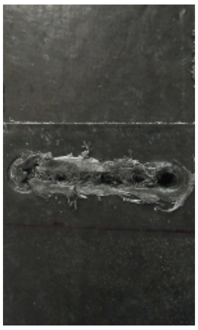

Fig. 2. Weld joint obtained at RS = 1600 rpm, WS = 31.5 mm/min and TA = 3°.

rameters were determined in such a way that acceptable welds were produced. Figs. 1 and 2 show two unacceptable welds produced at certain level of process parameters beyond the working ranges of parameters.

The FSW process parameters and their levels are given in Table 1.

2.2 Materials and equipment

Plates of PP composites with 20 wt% CF and 101 mm×50 mm×4 mm size were used as the parent material to be lap welded in this investigation. On a vertical milling machine, a clamping fixture as shown in Fig. 3 was used to keep the sheets together.

A cylindrical-conical grooved pin tool as shown in Fig. 4 was used in the experiments. This tool, with a 12 mm diameter shoulder and a pin of a diameter of 4 mm and 7.7 mm height was made from high speed steel (HSS) and heat treated to a hardness of 60 HRC. The selection of this pin profile was

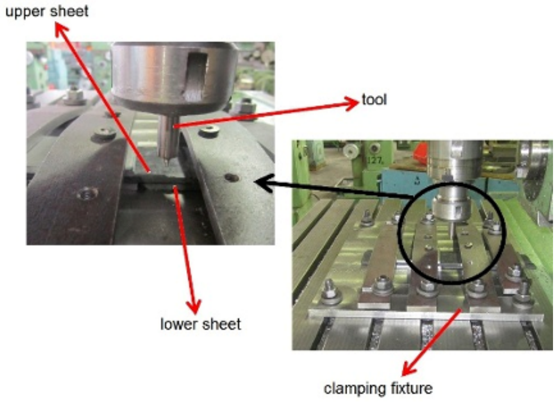

Fig. 3. Arrangement of the clamping fixture, sheets and the tool used.

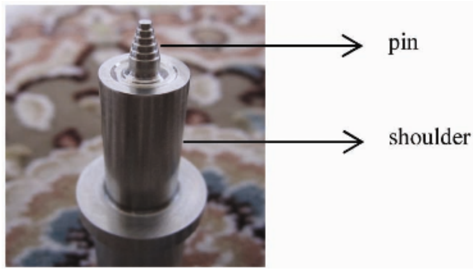

Fig. 4. Tool used in FSW experiments.

based on the previous works conducted by other researchers [26-28].

2.3 Design of experiments

In order to study process parameters effect on weld TSS of the joints, the statistical technique of Taguchi experimental design was selected. The steps of the Taguchi experimental design are: (a) selecting the response (output variable) to be optimized, (b) identifying the factors (input variables) affecting response and choosing the levels of these factors, (c) selecting the appropriate orthogonal array, (d) assigning factors to the columns of the array, (e) conducting experiments randomly to minimize systematic errors, (f) checking the results using signal to noise ratio (S/N ratio) and analysis of variance (ANOVA), (g) determining the optimal process parameters, (h) performing confirmation tests [29].

2.4 Tensile-shear strength test specimen preparation

The TSS test specimens with the dimensions given in Fig. 5 were prepared after welding according to ASTM D5868 standard [30] from the middle of the welded plates to eliminate the start and end effects of the welding process. TSS tests were conducted using a SANTAM Universal Testing Machine-STM-150 keeping the cross-head speed at 2 mm/min. during the loading condition. Fig. 6 shows the tensile test setup.

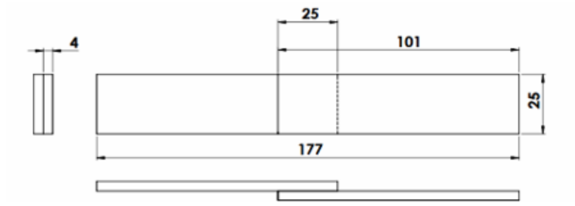

Fig. 5. Lap shear test specimen geometry and dimensions (mm) [30].

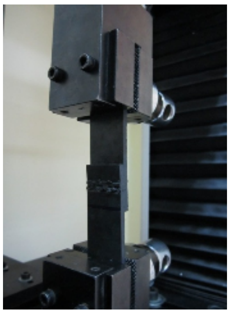

Fig. 6. Specimen and fixture during TSS test.

3. Results and discussion

3.1 Signal to noise ratio

Tensile-shear strength is the response or characteristic considered in this work to describe the quality of the FSW joints. In order to assess the effect of process parameters on this response, the means and S/N ratios for each process parameter should be calculated. According to the Taguchi method, S/N ratio is the ratio of signal, representing desirable value i.e., mean of output characteristics and the noise representing the undesirable value i.e., squared deviation of the output characteristics. Therefore, the S/N ratio is the ratio of the mean to the square deviation. Taguchi uses S/N ratio to measure the quality characteristic deviating from the desired value [31]. It is denoted by η ; its unit is dB and is defined as [19]:

$$\eta = -10\mathrm{Log}(\mathrm{M.S.D}) \tag{1}$$

where, M.S.D is the mean square deviation for the output characteristic.

Taguchi defines three categories of quality characteristics in the analysis of S/N ratio, i.e. the lower-the-better, the larger-the-better and the nominal-the-better. The S/N ratio for each process parameter is computed based on S/N analysis. Regardless of the category of the quality characteristics, a larger S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of process parameter is the level of highest S/N ratio [32]. In this research, in order to maximize the weld TSS (response), the S/N ratio was selected according to the criterion of the larger-the-better. The M.S.D for the larger-the-better quality is expressed as [19]:

Table 2. Experimental data for TSS.

Exp. no.	Input parameter			Response			TSS (MPa) (Mean)	S/N ratio for TSS (dB)
	RS	WS	TA	1	2	3		
1	1	1	1	5.04	4.89	5.49	5.14	14.21
2	1	2	2	4.46	4.35	5.77	4.86	13.73
3	1	3	3	5.45	6.24	5.02	5.57	14.91
4	2	1	2	5.33	5.57	6.44	5.78	15.23
5	2	2	3	4.10	4.90	5.67	4.89	13.78
6	2	3	1	5.23	6.67	5.53	5.81	15.28
7	3	1	3	5.02	5.97	5.84	5.61	14.97
8	3	2	1	4.77	4.93	5.21	4.97	13.92
9	3	3	2	6.02	6.21	5.95	6.06	15.64

Table 3. The mean S/N response table for TSS.

Symbol	Mean S/N ratio (dB)				
	Level 1	Level 2	Level 3	Delta	Rank
RS	14.29	14.77	14.85	0.56	2
WS	14.81	13.82	15.28	1.47	1
TA	14.48	14.87	14.56	0.40	3

$$\mathrm{M.S.D} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{T_i^2} \tag{2}$$

where, n is the number of tests and T_i is the value of weld strength of the ith test.

In this study, 9 values for TSS and 9 values for S/N ratio were obtained. In order to evaluate the influence of the welding parameters on TSS, the means and S/N ratios for each welding parameter were calculated. Lap welding of the plates was performed randomly according to Table 2. Each run (Experiment number) was repeated three times to minimize the noise factor. Table 2 shows the experimental results for TSS and the corresponding S/N ratios which were calculated by using Eqs. (1) and (2). The effect of the FSW process parameters on mean of S/N ratios for the design of the experiments shown in Fig. 7 was obtained by using MINITAB statistical software [33]. S/N ratio of the parameters when they change from lower to higher levels is also given in Table 3.

According to the main effects plot for S/N ratios shown in Fig. 7, the optimum values for RS, WS and TA were at levels 3, 3 and 2 respectively i.e. RS3WS3TA2.

As the experimental design is orthogonal, it is possible to divide each welding parameter into three levels. For instance, the mean S/N ratio for RS at level 1, 2 and 3 can be computed with mean S/N ratios for the trials 1 to 3, 4 to 6 and 7 to 9, respectively [16]. Table 3 shows the mean S/N ratio for each level of the welding parameters. The total mean S/N ratio of the nine experiments was 14.63 dB.

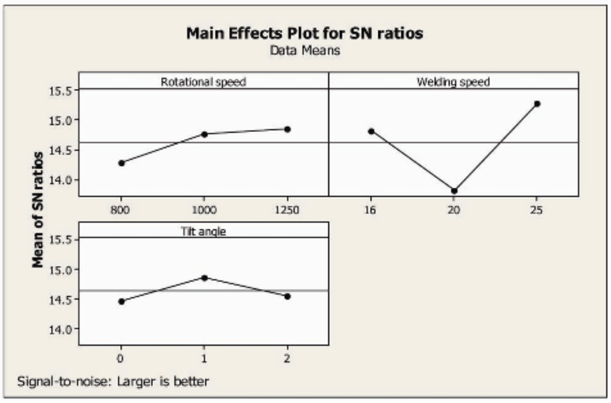

Fig. 7. The main effects plot for S/N ratio.

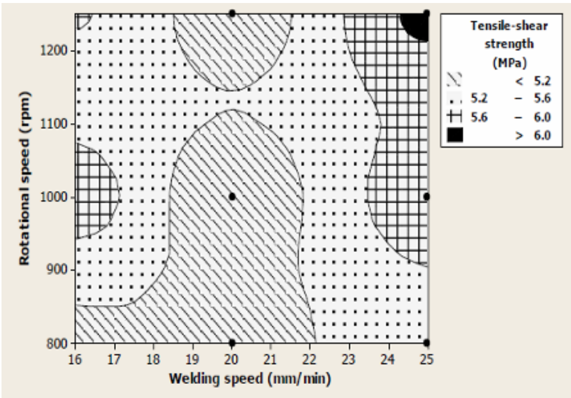

Fig. 8. Contour plot for the effect of WS and RS on TSS.

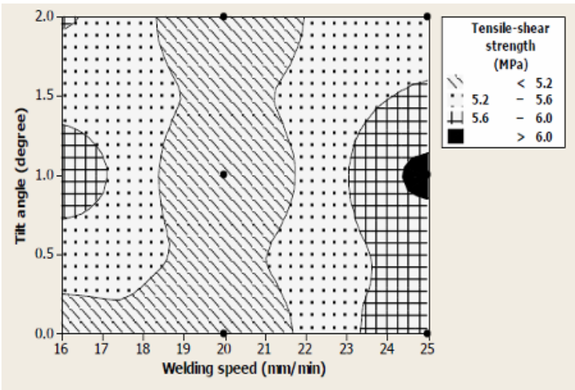

Fig. 9. Contour plot for the effect of WS and TA on TSS.

According to the results shown in Table 2, the contour plots of Figs. 8−10 show the influence of the FSW welding parameters on the weld TSS. These contour plots have been drawn using the MINITAB software for Taguchi method.

All the black zones in the graphs show the maximum TSS zone. From Fig. 8, it is evident that at high welding speeds (25 mm/min and higher) and high rotational speeds (1250 rpm and higher), maximum TSS can be obtained. Black zones in Figs. 9 and 10 show similar results.

Table 4. Results of the ANOVA for TSS.

Symbol	DF	SS	MS	F	P	SS′	PC (%)
RS	2	0.55307	0.27653	16.23	0.058	0.51899	12.29
WS	2	3.37095	1.68548	98.91	0.010	3.33687	79.06
TA	2	0.26245	0.13123	7.70	0.115	0.22837	5.41
Error	2	0.03408	0.01704			0.13633	3.23
Total	8	4.22056					100

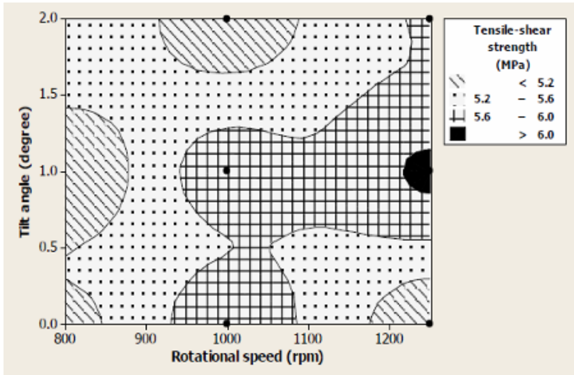

Fig. 10. Contour plot for the effect of RS and TA on TSS.

3.2 Analysis of variance

Analysis of variance can be used to determine the relative importance of the effect of the welding parameters on the weld strength. The relative importance of the parameters is needed so that their optimal combination levels can be assessed [34].

The results of ANOVA for the TSS of means were calculated which are shown in Table 4. The F-test was performed to study the importance of the welding parameters. Larger F values indicate that the variation of the welding parameters produces a big change on the rank [34]. The results of ANOVA reveal that the evaluated welding parameters are significant factors affecting the TSS of the FSW joints.

3.3 Percent contribution

Percent contribution indicates the relative power of a factor to reduce variation. For a factor with a higher percent contribution, a small variation will have a great influence on the performance [34]. The percent contribution of the welding parameters on the welds TSS is shown in Table 4 and Fig. 11. It is observed that WS is the most important welding parameter affecting the weld strength. In this study, WS was a highly important factor whereas TA was a less important one. The most important factor of FSW that influences the weld strength is WS with 79.06% contribution. Only 0.03408 of the variance was inducted by experimental errors which prove that the experimental design was very successful.

Table 5. Results of the confirmation tests for TSS.

	Optimal welding parameters	
	Prediction	Experiment
Parameter levels	RS3, WS3, TA2	RS3, WS3, TA2
TSS (MPa)	6.13	6.06
S/N ratio (dB)	15.74	15.64

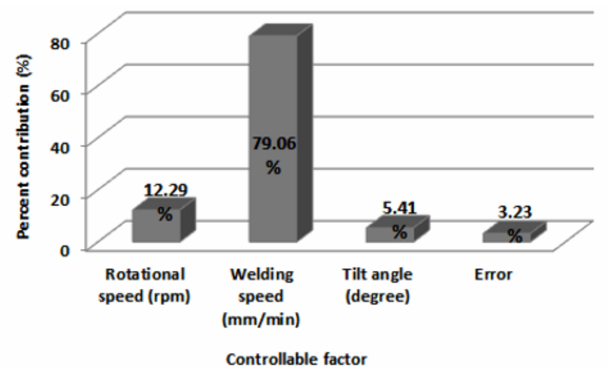

Fig. 11. Percent contribution for FSW process parameters.

3.4 Confirmation test

Once the optimal levels of the welding parameters were selected, the final step is to predict and verify the quality characteristic using the optimal level of the welding parameters. The predicted S/N ratio ($\hat{\eta}$) using the optimal level of the welding parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{O} \left(\bar{\eta}_i - \eta_m \right) \tag{3}$$

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 affect the quality characteristic. Table 5 shows the comparison of the predicted and the actual weld TSS using the optimum welding parameters. Good agreement between the predicted and the actual weld TSS is observed.

4. Conclusions

In this study, the applicability of FSW on PP composite with 20 wt% CF sheet was studied by using the Taguchi method. The following results were obtained:

(1) The L9 Taguchi orthogonal array was successfully employed for FSW of PP composite with 20 wt% CF sheets.

(2) The welding speed was the most significant welding process parameter whereas the tilt angle was the least significant one affecting the tensile-shear strength.

(3) The percentage of contributions of the welding speed, rotational speed and tilt angle for tensile-shear strength is 79.06%, 12.29% and 5.41%, respectively.

(4) For maximum weld tensile-shear strength, the optimum values of welding speed, rotational speed and tilt angle were 25 mm/min, 1250 rpm and 1 degree, respectively.

Nomenclature

η : S/N ratio
M.S.D : Mean square deviation
n : Number of tests
T_i : Value of the weld strength of the ith test
DF : Degree of freedom
SS : Sum of squares
MS : Mean square
F : F-test
P : Probability that exceeds 95% confidence level
SS' : Pure sum of squares
PC(%) : Percent contribution
$\hat{\eta}$: Predicted S/N ratio
η_m : Total mean S/N ratio
$\bar{\eta}_i$: Mean S/N ratio at the optimal level
O : Number of the main design parameters

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