

Research Article

Optimization of Stamp Forming Process for Thermoplastic Composites

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Abstract: The present study is focused on the development of a two-dimensional stamping method for the manufacturing of fiber reinforced composites with thermoplastic matrix resins. Materials investigated are carbon fiber reinforced polyamide-6. Taguchi L_{16} orthogonal array is used in split-plot designs. The processing conditions include thermoforming temperature, mold temperature, pressure and time, required to establish high-quality parts. From the experimental results, we derive a set of best combination, A1 (90°), B2 (263°C), C1 (105°C), D1 (33 kg/cm²) and E2 (48 sec) and carry out an estimated equation for the short-beam shear strength. The results have described the correlations between processing parameters and shear stress. Finally, for verifying the prediction ability of the estimated equation, the confirmation experiments are conducted. The confirmation test result is 48.67 kg/mm², fall in the confidence interval. It shows that the prediction ability of estimated equation and the repetition of the experimental results has confirmed and accepted by the tests.

Keywords: L_{16} orthogonal array, split-plot designs, thermoplastic composites

INTRODUCTION

In recent years research in fiber-reinforced thermoplastics composites has been receiving growing attention from investigators because of their increasing applications in aerospace, automobile and mineral processing industries. There exists an abundance of fiber-reinforced thermoplastics that exhibit material properties such as strength and modulus those are either comparable to or better than traditional metallic materials (Michael *et al.*, 2004). These materials can exhibit the same strength properties as sheet steel, but at a fraction of the weight (Dweib and O'Bradaigh, 1998). Since joining of thermoset composites through structural bonding or mechanical fastening is tedious, labor intensive and time consuming (Stavrov and Bersee, 2005), which generally involves forming of dry fiber woven performs (Boisse *et al.*, 2011; Cao *et al.*, 2008; Peng and Rehman, 2012) prior to resin infiltration and cure processing.

Thermoplastic composite technology, however, seems more suitable for producing. Thermoplastic composites with fabric reinforcement can be processed rapidly from intermediate materials using a melting and solidification procedure. They bring the great advantage that they are more easily molded in mass production quantities than are reinforced thermosets. Also, Since thermoplastics are fully reacted high molecular resins that do not undergo chemical reactions during cure, the processing for these materials is theoretically simpler

and faster (Greco *et al.*, 2007; Trudel-Boucher *et al.*, 2006). A typical cycle time for manufacturing a thermoplastic part through rubber forming for instance is 5-8 min, whereas the curing time of a thermoset resin is in the order of hours.

Considered here is the stamp forming of carbon fiber/polyamide-6 (CF/PA-6) composites that is analogous to match die sheet metal stamping. Taguchi L_{16} orthogonal array is used in split-plot designs. The present study will focus on the processing conditions (factors), e.g., the thermoforming temperature, mold temperature, mold hold-down pressure and time, required to give high-quality right-angle parts are established. Through this experiment and data analysis, can determine the optimal process condition and establish quality characteristics of the Short-Beam Strength (SBS) prediction mode.

MATERIALS AND METHODS

Experiment design: This study focuses on the optimization of stamp forming process for thermoplastic composite. There are a number of factors that influence the forming of fiber, reinforced composite materials. One of the most important factors is the effect that temperature has on the formability of the material (Czigany *et al.*, 2000). Trudel-Boucher *et al.* (2006) have been investigated the stamp forming process for simple mold geometry. The influence of stamping pressure, mold temperature, loading rate and

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Table 1: Description of factor and level selection

Level change	Factor	Level	
		1	2
1's the most difficult	B : forming temperature (°C)	248	263
2's	A : mold angle	90°	120°
Difficult	C : mold temperature (°C)	105	115
3's	D : hold-down pressure (kg/cm ²)	33	39
Less difficult	E : pressure time (sec)	36	48

Table 2: L₁₆ orthogonal array allocation and trial sequence

Group factor	Trial	G1			G2				G3				G4					SBS
		B	e1	e1	A	e2	C	e2	D	e3	e3	E	e3	e3	e3	e3		
1	13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	42.96	
2	14	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	44.75	
3	15	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	44.75	
4	16	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	49.49	
5	11	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	41.49	
6	12	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1	40.51	
7	10	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	40.02	
8	9	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2	42.47	
9	8	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	54.39	
10	7	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	48.02	
11	2	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	45.24	
12	1	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2	49.16	
13	3	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	45.08	
14	4	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2	44.75	
15	6	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	43.12	
16	5	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	46.55	

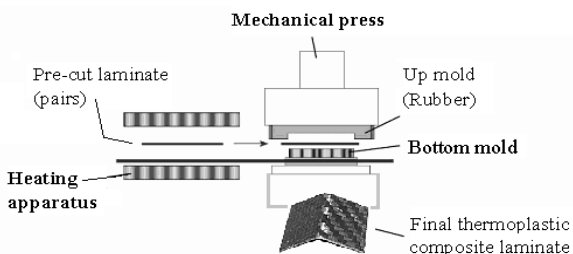


Fig. 1: Schematic of forming equipment

holding time, have been determined on the void content and void distribution. They have shown that void distribution was very similar for most stamping pressure. In this experiment, we follow the above parameters. Description of the parameters and their level are shown in Table 1. According to the degree of difficulty on level change, the levels of the factors are expressed as 1's, 2's and 3's.

L₁₆ orthogonal array is used in split-plot designs, allocation and trial sequence shown as Table 2. The groups correspond to plots in split-plot design. The whole plot can be allocated to Group 1 (G1), subplots to Group 2 (G2), sub-subplots to Group 3 (G3) and sub-sub-subplots to Group 4 (G4). 1's, 2's and 3's factors could be allocated to each group, which make the level of each factor are treated repeatedly 8 times.

Materials and experiment process: The stamp-forming process was performed using various

processing conditions as shown in Table 2. The schematic of forming equipment is shown in Fig. 1. CF/PA-6 composite sheets are used in the present experiment, provided by the Applied Fiber System Inc., USA. The billet, 914×914×1 mm (length × width × thickness), should be cut into the size of 10×7×1 mm held for forming. Thirty two pieces is needed and stacked 2 pieces into one pairs. Each pairs is put into the heating apparatus first until the forming temperature is reached. The mould is heated prior to the first forming cycle and then used continuously in order to maintain as uniform a temperature as possible during the cycles. The heated pairs is positioned between the up and bottom mould. While cooling down to mould temperature the matrix solidifies. After the press is opened, the finished laminate can be removed. Transport of the pairs from the heating source to the press and the thermoforming operation itself must be carried out speedily to allow for completion of the pressing operation before the thermoplastic falls below its re-crystallization temperature. Otherwise fabric shearing will be impeded.

To evaluate the strength, the Short-Beam Strength (SBS), as mentioned in the ASTM D2344/D2344M-00 (2006) is calculated using Eq. (1):

$$\tau^{sbs} = 0.75P/bh \tag{1}$$

where,

- τ^{sbs} = The short-beam strength (kg/mm²)
- P = The maximum load observed during the test (kg)
- b = The width of the specimen (mm)
- h = The height of the specimen (mm)

The test specimens for the SBS test were rectangular shaped and with the following nominal dimensions: 1"×0.25". After the solidified laminates are completed, a minimum of three specimens per condition was tested. The Short-Beam Strength (SBS) tests are conducted on Model-4206 testing machine, made by INSTRON Ltd. U.S.A.

RESULTS AND DISCUSSION

In the present experiment, the SBS test records are shown in Table 1. In order to understand a concrete visualization of impact of various factors and their interactions; it is desirable to develop Analysis of Variance (ANOVA) table to find out the order of significant factors as well as interactions. This analysis was undertaken for a level of confidence of significance (Sig.) of 5%. If the Sig calculated is less than 0.05, it is an indication that the statistical test is significant at the confidence level selected. If not, it indicates that the statistical test is not significant.

The results of ANOVA for the Taguchi in split-plot method experiment are tabulated in Table 3. There are two classes of effects that we are interested in: Main Effects and Interactions. It shows that main effects, B (Forming Temperature) and the interaction AB, AC, AD, BC are significant at the Sig p<0.05 levels.

Using an α of 0.05, we have that $F_{0.05}(1, 10) = 4.96$. The F test is a test to determine the overall significance of the model and not just of one individual coefficient. Referring to Table 3 it may be seen that RSQ value for response is 88.27% which suggests that the model provides a good relationship between the independent variables and the response (SBS). Therefore, the best combination of factor levels can be determined in accordance with the main effect and interaction simultaneously.

To illustrate Taguchi’s approach, observe in Fig. 2 the main effect plot and the SBS data in Table 4. In Fig. 2, it is apparent that one might suggest choosing factor B at its high level in order to maximize the SBS. The best level of forming temperature is B2, forming temperature 263°C.

The interaction plots are very useful for interpreting interaction effects and confirm the significance of AC, AB, AD, BC interaction as stated below. Interaction occurs when one factor does not produce the same effect on the response at different levels of another factor. Therefore, if the lines of two factors are parallel, there is no interaction. On the contrary, when the lines are far from being parallel, the two factors are interacting.

Table 3: The results of ANOVA for Taguchi in split-plot designs

Source	S.S.	df.	M.S.	F0
B	55.76	1	55.760	22.815
AB	14.42	1	14.420	5.900
AC	75.56	1	75.560	30.917
AD	26.09	1	26.090	10.675
BC	12.06	1	12.060	4.935
Error	24.44	10	2.444	
Total	208.33	15		
RSQ	0.8827			
RSQ (Adj.)	0.8240			

S.S.: Sum of square; M.S.: Mean of square

Table 4: Average SBS of the factor B

Factor	SBS (means)
B1	43.31
B2	47.04

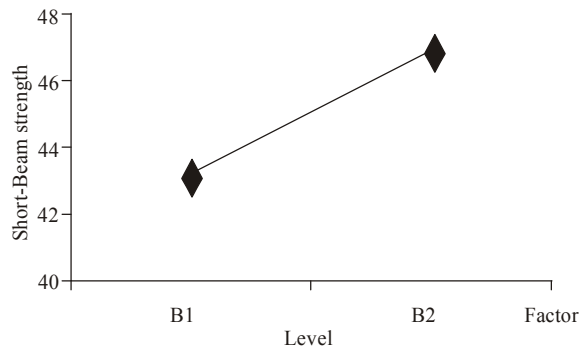


Fig. 2: Main effect plot for SBS (factor B)

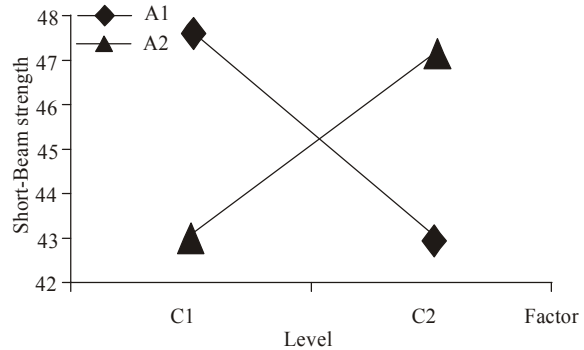


Fig. 3: Main effects plot for SBS (AC interaction)

As can be seen from the interaction plots of AC (Fig. 3), AB (Fig. 4), AD (Fig. 5), BC (Fig. 6), the forming temperature is in high level, there will be a higher SBS. Therefore, if fixed B2 (263°C), we can see a higher SBS in A1 (90°), C1 (105°C), D1 (33 kg/cm²) and E2 (48 sec)

By the results of the above analysis, the best combination of the parameters will be A1 (90°), B2 (263°C), C1 (105°C), D1 (33 kg/cm²) and E2 (48 sec). We extract the parameters of the estimated equation with the coefficients function. The final model for SBS so developed is expressed as:

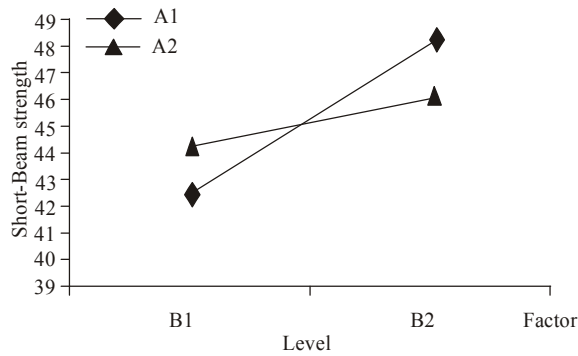


Fig. 4: Main effects plot for SBS (AB interaction)

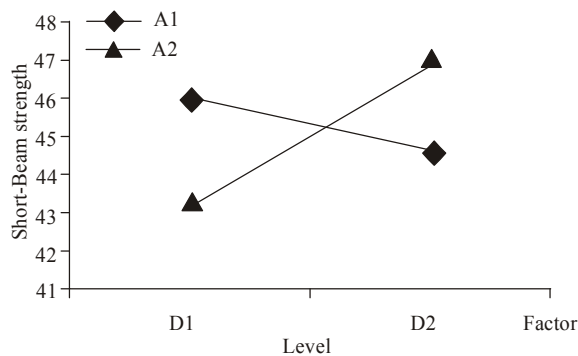


Fig. 5: Main effects plot for SBS (AD interaction)

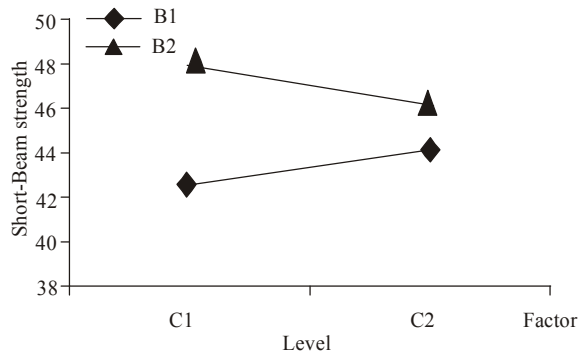


Fig. 6: Main effects plot for SBS (BC interaction)

Table 5: Comparisons of experimental trials

Best combination of the parameters	SBS		
	Prediction	Confirmation	Prediction interval
(A1, B2, C1, D2, E2)	50.35	48.67	(46.552, 54.123)

$$SBS = 45.17 + 1.87B - 0.95 (A*B) + 2.27 (A*C) + 1.28 (A*D) - 0.87 (B*C) \quad (2)$$

AB, C, D = 1 or -1

Confirmation experiment: The confirmation experiment is the final test in the design of experiment process. The purpose of the confirmation experiment is to validate the conclusions drawn during the analysis

phase. It is performed by conducting a new set of factor settings to predict the SBS. The optimal SBS obtained by taking into account the influential factors within the evaluated best combination. Therefore, the predicted optimum SBS Eq. (2) was calculated by considering individual effects of the factors A1, B2, C1, D1, E2. The optimal SBS was computed as 50.35 kg/mm².

The confidence interval was employed to verify the quality characteristics of the confirmation experiments. The confidence interval for the predicted optimal values is calculated also. In this study, three confirmation experiments (r = 3) were carried out to evaluate the performance of experimental trials for SBS under optimal conditions. The confidence interval was calculated as (46.552, 54.123). With a 95% confidence level, the confirmation test results were 48.67, fell in the confidence interval. Therefore, the optimization for SBS was achieved using the Taguchi method at a significance level of 0.05. The experiment condition of the best combination of the parameters was done repeatedly. The data from the confirmation results are shown in Table 5. This test have confirmed the prediction ability of estimated equation and accepted the repetition of the experimental results.

CONCLUSION

In this study, stamping trials were performed with thermoplastic composite materials. The forming conditions were carried out by the Taguchi method in split-plot designs. The following can be concluded from the present study:

- The best combination of the parameters are A1, B2, C1, D1 and E2 i.e., mold angle (90°), forming temperature (263°C), mold temperature (105°C), hold-down pressure (33 kg/cm²) and pressure time (48 sec)
- The optimal SBS is 50.35 (kg/mm²)

Finally, for verifying the prediction ability of the estimated equations, the confirmation experiments were conducted. The confirmation test results were 48.67, fell in their confidence interval, respectively. It shown that the prediction ability of estimated equation and accepted the repetition of the experimental results have confirmed by the tests.

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