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Two-dimensional Stamp Forming Analysis for Thermoplastic Composites

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Abstract: Fiber-reinforced thermoplastics have been gaining popularity for many of the weight critical components in the aerospace and automotive industries. They offer the potential advantage because they are molded in mass-production more easily than are reinforced thermosets. In this study, the main purpose is focused on the two-dimensional stamp forming process for the manufacturing of carbon fiber reinforced polyamide-6. Two different mold angles (90°, 120°) are discussed. The experiments are conducted based on five factors (two levels each) split-plot design with Taguchi L_{16} orthogonal array. The processing conditions, e.g., the thermoforming temperature, mold temperature, pressure and time, required to give high-quality parts are established. By the results of the analysis of variance (ANOVA), this study derives the best set of the parameters and their estimated equations under different mold angle, respectively. The results have described the correlations between processing parameters and shear stress. Furthermore, for verifying the prediction ability of the estimated equations, the confirmation experiments are conducted. The confirmatory test results, 48.67 and 48.16 kg mm^{-2}, fall in their confidence interval, respectively. It shows that both of the prediction ability of estimated equation and the repetition of the experimental results have confirmed and accepted by the tests.

Key words: Thermoplastic composites, L_{16} orthogonal array, split-plot designs

INTRODUCTION

Fiber-reinforced thermoplastics have been gaining popularity as substitutions for many of the weight critical components in the aerospace and automotive industries (Mallick, 1993). 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 (Zampaloni *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). In response to driving forces requiring weight reduction in light-weight structures, a stamp forming process has been investigated using Glass Fiber (GF), Carbon Fiber (CF) and hybrid carbon-glass fiber fabrics impregnated with polyamide (PA) (Wakeman *et al*., 2005).

Since the combination of thermoset composites through structural adhesive is both time-consuming and labor-intensive (Stavrov and Bersee, 2005), which generally involves the dry forming of fibrous woven materials (Boisse *et al*., 2011; Cao *et al*., 2008; Peng and Rehman, 2011) performs post-mold resin infiltration and cure process. Thermoplastic composites with fabric reinforcement seem more suitable for producing and can be processed rapidly from intermediate materials using a melting and curing process. They offer the potential advantage because they are molded in mass-production more easily than are reinforced thermosets. Furthermore, the thermoplastics do not undergo any additional chemical reaction during cure, which theoretically makes the process simpler and faster (Greco *et al*., 2007; Trudel-Boucher *et al*., 2006).

Considered here is the stamp forming of carbon fiber/polyamide-6 (CF/PA-6) composites that is analogous to match die sheet metal stamping. This study describes an experimental study on the development of a two-dimensional stamp-forming method for the processing of CF/PA-6 composites with thermoplastic matrices, in which two different angle molds (90°, 120°) and a mechanical press are used. Split-plot designs are used in the experiments of Taguchi L_{16} orthogonal array. 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

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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. Stamping process by different angles, these results could be used as a further understanding about the relationships between the forming angle and strength. It also pointed out that, the estimated equation calculated from the stamping results of the two mold angle, when the preheating temperature is higher, obviously, can produce higher shear strength.

MATERIALS AND METHODS

Experiment design: The present study focuses on the processing conditions, e.g., forming temperature, mold temperature, mold pressure and time. Parameters selection and their level described as Table 1. L_{16} orthogonal array is used in split-plot designs, allocation and trial sequence shown as Table 2. According to the degree of difficulty on level change, Taguchi's orthogonal array applied to split-plot design, the levels of the factors are expressed as 1's, 2's and 3's. 1's factors defined as the level is the most difficult to change, 2's and 3's factors defined as difficult and less difficult respectively. The groups correspond to plots in split-plot design. The whole plot can be allocated to group 1, subplots to group 2, sub-subplots to group 3 and sub-sub-subplots to group 4. Column 1 allocated to group 1;column 2, 3, column 4, 5, 6, 7 and column 8, 9, 10, 11, 12, 13, 14, 15 allocated to group 2, 3, 4, respectively. 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.

Experiment materials and processing: 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.

Stamp forming process was carried out as shown in Table 1. Each heated pairs were positioned between the top and bottom mould (Fig. 1) halves in a press and

Table 1: Description of parameters selection and the degree of difficulty on level change

Factor	Level 1	Level 2	Description
1's			
Forming temperature (°C)	248	263	Material preheated by the oven. Changes in temperature within the oven mining randomized each factor level changes accordingly. In order to make uniform and consistent temperature within the oven, it should be extremely time-consuming waiting, resulting in increased costs
2's			
Mold angle	90°	120°	Temperature of the stamping machine is transmitted to the mold through the heat conduction. The conduction velocity is extremely slow, need to be waiting for a long time; when the replacement of the different angles' molds by the requirements of experimental design, mold replacement must wait for the mold heating and cooling operation, resulting in increase in the cost of waiting
Mold temperature (°C)	105	115	
3's			
Hold-down pressure (kg mm^{-2})	33	39	Can be controlled directly by the operation of the stamp forming machine
Pressure time (sec)	36	48	

1's, 2's and 3's factors defined as the degree of difficulty on level change

Table 2: L_{16} Orthogonal array allocation and trial sequence

Factor		B	e1	e1	A	e2	C	e2	D	e3	e3	E	e3	e3	e3	e3
No.	Trial	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	14	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	15	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	16	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
5	11	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
6	12	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
7	10	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
8	9	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
9	8	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	7	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
11	2	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
12	1	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
13	3	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
14	4	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
15	6	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
16	5	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1

A: Mold angle, B: Forming temperature, C: Mold temperature, D: Hold-down pressure, E: Pressure time, e1: First order error, e2: Second order error, e3: Second order error

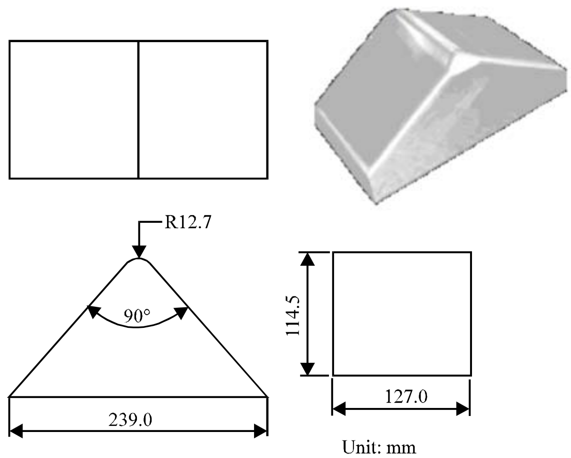

Fig. 1: Perspective view in the upper right and the other three for the 3D projection view of bottom mold

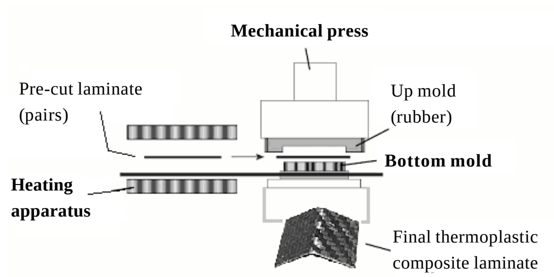

Fig. 2: Schematic diagram of the stamp forming process

closing the heated mould halves as quickly as possible. While cooling down to mould temperature the matrix solidified. After the press was 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. Processing diagram, shown as Fig. 2.

After the above-mentioned process, 16 solidified laminates were completed. The Short-beam Strength (SBS) tests are conducted on model-4206 testing machine, made by INSTRON Ltd. USA. According to the ASTM standard, the test specimens for the SBS test were rectangular shaped and with the following nominal dimensions: 1×0.25 inch. From the maximum force (P, kg), the inter-laminar shear strength (F, kg mm^{-2}) was calculated as follows Eq. 1:

$$F = 3P/4wt \quad (1)$$

where, w and t are the width and thickness of the specimen, respectively. A minimum of three specimens per condition was tested. According to the reference standard (ASTM, 2006), the SBS test is suited for comparative testing of composite materials, provided that failures occur consistently, that is in the same mode. The SBS test results are shown in Table 3.

RESULTS AND DISCUSSION

In the present experiment, mold angle is a qualitative factor, which may be one of the specifications of the product, not the process parameters. Therefore, this study needs to explore these two angles to build their response equation, to serve as the basis to explore the processing of different angles or shapes in the future. Next, the experiment uses the SBS as the response variable, comparing the two forming process under the different mold angles, to discuss the optimum parameter model.

Model of the mold angle 90-degree: The data below, resulted from measuring the SBS under mold angle 90°. Table 4 is extracted by using the data in Table 2, 3, i.e., the data in the column 3 (factor B) of Table 2 is allocated as Table 1.

The analysis of variance (ANOVA) is the statistical treatment most commonly applied to see which process factors significantly affect the process responses. The variance is the amount of deviation degree, which is obtained by finding the sum of squares of F-value between a set of data and actual value. The Sig. means the significance, which is calculated from the experimental results. Then, it was compared to the given critical significance level 0.05 representing significance levels at a 95% confidence interval. 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 5.

The test statistic is the F value of 10.993 and 7.152. Using an α of 0.05, the results of the test have met the significance level ($F_{0.05(1,A5)}$ = 6.608). The F test is a test to determine the overall significance of the model and not just of one individual coefficient. There are two classes of effects that this research is interested in: Main Effects and Interactions. It shows that both main effects, B (Forming Temperature) and C (Mold Temperature), are significant at the $p<0.05$ levels, yet the interaction is not. Therefore, the best combination of factor levels can be determined in accordance with the main effect. The best combination of factor levels can display by the main effects plot for SBS, as shown in Fig. 3.

Table 3: Short-beam strength test results by L_{16} orthogonal array experiment

Factor			Factor			Factor			Factor		
No.	Trial	SBS	No.	Trial	SBS	No.	Trial	SBS	No.	Trial	SBS
1	13	42.96	5	11	41.49	9	8	54.39	13	3	45.08
2	14	44.75	6	12	40.51	10	7	48.02	14	4	44.75
3	15	44.75	7	10	40.02	11	2	45.24	15	6	43.12
4	16	49.49	8	9	42.47	12	1	49.16	16	5	46.55

Table 4: Short-beam strength test records under mold angle 90°

Factor			Factor			Factor			Factor		
No.	Trial	SBS	No.	Trial	SBS	No.	Trial	SBS	No.	Trial	SBS
1	13	42.96	5	11	41.49	9	8	54.39	13	3	45.08
2	14	44.75	6	12	40.51	10	7	48.02	14	4	44.75

Table 5: Results of ANOVA for Taguchi in split-plot designs under mold angle 90°

Source	Sum of squares	Degree of freedom	Mean square	F-value
B	63.4500	1	63.45	10.993
C	41.2800	1	41.28	7.152
Error	28.8600	5	5.77	
Total	133.5900	7		
R^2	0.7840			
Adjusted R^2	0.6976			

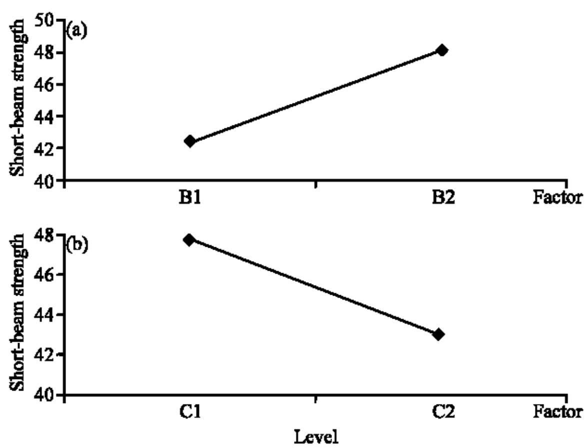

Fig. 3(a-b): Main effects for SBS in the case of mold angle 90° (a) Main effects of B (forming temperature) and (b) Main effects of C (mold temperature)

As can be seen in the above plots, under the mold angle 90°. It appears that the best result is obtained when each of the factors: B2 and C1 is at their high level. Thus, the best combination of factors can be obtained, i.e., when the mold angle is 90°, the best combination of the parameters will be B2 (263°C) and C1 (105°C). The following estimated equation (Eq. 2) is the model under mold angle 90° for the response variable SBS:

$$SBS = 45.24+2.82B-2.29C. \quad B.C = 1 \text{ or-}1 \qquad (2)$$

Model of the mold angle 120-degree: The data below, resulted from measuring the SBS under mold angle 120°. Table 6 is extracted by the same way, similar as the paragraph of Mold Angle 90°. The results of ANOVA for the experiment are tabulated in Table 7.

There are concluded that the main effects B (Forming Temperature), C (Mold Temperature), D (Mold Pressure) and the interaction BC are significant. Therefore, the best combination of factor levels can be determined in accordance with the main effects and interaction effect simultaneously. This interaction plot confirms the significance of 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. In the case of BC interaction, the Main Effects Plot for SBS is shown in Fig. 4, the molding temperature is in high level, there will be a higher SBS. Therefore, high level molding temperature B2 (263°C), which is one of the best factors. Then, if fixed B1, there is a higher SBS in C2 (105°C). Then, to observe the main effect of factor D, referring to Fig. 4, the best factor mold pressure level is D2, mold pressure 39 kg cm^{-2}.

By the results of the above analysis, the best combination of the parameters will be B2 (263°C). C2 (115°C) and D2 (39 kg cm^{-2}). The following estimated equation (Eq. 3) is the model under mold angle 120° for the response variable SBS:

$$SBS = 45.10+0.92B+2.06C+1.82D-0.88BC \quad B.C. \; D1 \text{ or-}1 \qquad (3)$$

Confirmation experiment: In order to verify the prediction ability of the estimated equations, the final step of the Taguchi method is the confirmation experiments conducted for examining the quality characteristics. The model used in the confirmation tests is defined with the

Table 6: Short-beam strength test records under mold angle 120°

Factor No.	Trial	SBS	Factor No.	Trial	SBS	Factor No.	Trial	SBS	Factor No.	Trial	SBS
3	15	44.75	7	10	40.02	11	2	45.24	15	6	43.12
4	16	49.49	8	9	42.47	12	1	49.16	16	5	46.55

Table 7: Results of ANOVA for Taguchi in split-plot designs under mold angle 120°

Source	Sum of squares	Degree of freedom	Mean square	F-value
B	6.7300	1	6.73	14.694
C	33.9500	1	33.95	74.127
D	26.4300	1	26.43	57.707
BC	6.1600	1	6.16	13.450
Error	1.3700	3	0.46	
Total	74.6400	7		
R^2	0.9816			
Adjusted R^2	0.9570			

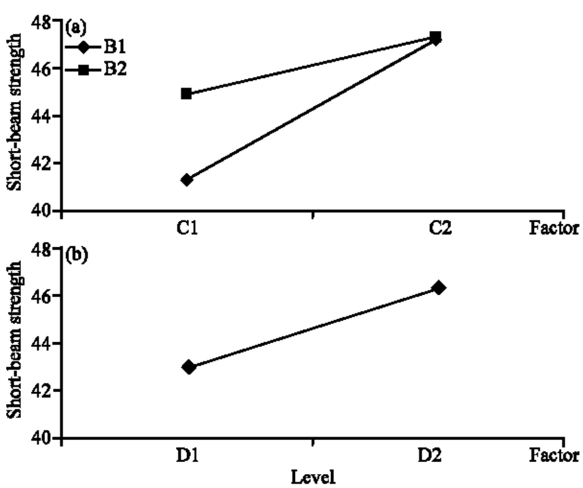

Fig. 4(a-b): Main effects for SBS in the case of mold angle 120° (a) Interaction plot between B×C, (b) Main effects of D (mold pressure)

main effect generated by the control factors (processing conditions). The optimal SBS obtained by taking into account the influential factors within the evaluated best combination. Therefore, the predicted optimum SBS (Eq. 2 and 3) was calculated by considering individual effects of the factors (A1, B2, C1, D2, E2) and (A2, B2, C2, D2, E2). The optimal SBS (90°) was computed as 50.35 kg mm^{-2} and another one (120°) was 49.02 kg mm^{-2}.

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) and (47.312, 50.717). With a 95% confidence level, the confirmatory test results were 48.67 and 48.16, 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 confirmatory test results are shown in Table 8. These tests have confirmed the prediction ability of estimated equation and accepted the repetition of the experimental results.

Table 8: Comparison between confirmatory test results and theoretical prediction under the best combination of the parameters

Mold angle	Best combination of the parameters	SBS (kg mm^{-2}) Prediction	Confirmation	Prediction interval
90°	(A1, B2, C1, D2, E2)	50.35	48.67	(46.552, 54.123)
120°	(A2, B2, C2, D2, E2)	49.02	48.16	(47.312, 50.717)

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. Stamping by different angles, this result can be used as a further understanding about the relationship between the forming angle and strength. In the performed experimental trials using Taguchi L_{16} orthogonal arrays, obtain two sets of best combination of the parameters. It was found that the main effects of mold angle 90°, B (Forming Temperature) and C (Mold Temperature), are significant at the $p<0.05$ levels, yet the interaction is not. From their main effect plot, this study obtains the best combination of the parameters, B2 (263°C) and C1 (105°C). Similarly, from the condition of mold angle 120°, there get another best combination of the parameters, B2 (263°C), C2 (115°C) and D2 (39 kg mm^{-2}).

From both estimated equation, the short-beam shear stresses measured at the specimens from different mold angles were almost equal. By comparing specimens shear results, it was observed that the forming temperature and mold temperature were the dominating parameters, no matter what kinds of mold angle are. It appears that temperature is the most decisive factor, especially the forming temperature.

Finally, for verifying the prediction ability of the estimated equations, the confirmation experiments were conducted. The confirmatory test results, 48.67 and 48.16, 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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