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Delamination During Drilling in Polyurethane Foam Composite Sandwich Structures

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The objective of this paper is to study the influence of drilling velocity, feed rate, and flank length on the delamination of polyurethane foam sandwich structures. A Taguchi-based design of experiments was used to assess the importance of the drilling parameters, and scanning electron microscopy (SEM) was used to assess the damage from drilling. The drilling of sandwich structures results in significant damage caused by delamination and surface roughness around the drilled holes. The drilling process was evaluated based on a factor called the delamination factor, which is defined as the ratio of the maximum diameter of the damage zone, measured using SEM, to the standard hole diameter (drill diameter). Analysis of variance of the experimental results showed that cutting speed was the most significant parameter among the controllable parameters during drilling of sandwich specimens followed by flank length and feed rate. Finally, confirmation tests were performed to make a comparison between the experimental results and the correlation results. The damage mechanisms are explained using SEM.

Keywords cutting speed, drilling, feed rate, SEM, Taguchi

1. Introduction

Sandwich construction is widely used due to its ability to provide high bending stiffness, fatigue strength, and buckling strength coupled with lightweight advantages (Ref 1-4). Hence, sandwich structures are in great demand in aerospace, aircraft, domestic, and other applications where high specific strength and specific stiffness to weight ratios are required. Fiber-reinforced sandwich structures provide tailored properties as a result of changing fiber reinforcement in the face sheet and the quality of the foam. During the past decade, a number of articles have appeared on the investigation of mechanical properties, fabrication, modeling, and applications of sandwich structures (Ref 5, 6). When life-cycle operating costs are evaluated in all of the application areas, sandwich materials are found to be cost effective in the long term. Extensive use of sandwich structures has resulted in many different manufacturing processes and machining conditions. They are found to be damaged when they are machined. Drilling is one of the very widely used machining processes for sandwich structures for assembly purposes. Typical problems are encountered in the drilling of sandwich structures, including delamination of the sandwich structures, fiber pullout, uneven powdery chips, etc. Delamination of sandwich structures reduces the strength against fatigue, resulting in a poor assembly tolerance that affects the integrity of the sandwich structure (Ref 7).

Several researchers have addressed drilling delamination both analytically and experimentally for fiber-reinforced plastic laminates (Ref 8-10). However, the drilling damage problem of foam-cored sandwich structures is scarcely reported in the open literature. The objective of this paper is to investigate the drilling damage characteristics of polyurethane sandwich panels and the effect of drill tool speed, feed rate, and flank length on the quality of the holes drilled. This paper also incorporates the techniques of Taguchi (Ref 11, 12) in planning and executing experiments in a controlled way and in analyzing the data to obtain information about the behavior of a given process. These techniques use orthogonal arrays to design the experimental test matrix with respect to critical factors. The significance of the factors is then identified based on analysis of variance (ANOVA).

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2. Experimental Procedures

2.1 Materials

The sandwich specimens used in this study consisted of glass/polyester face sheets and a polyurethane (PU) foam core. The primary chemicals used to produce the PU foam were methylene diisocyanate (MDI) and polyether polyol (PP). The specimens were prepared according to manufacturers' recommendations. The specimen preparation procedure was reported previously (Ref 1).

2.2 Preparation

The following procedure was used to fabricate the sandwich specimens:

1. Equal amounts of MDI and PP liquids were measured in separate clean and dry glass cups to produce PU foam of density 0.8 g/cm^3.
2. The inner surface of a wooden die was fabricated for the specimens (200 × 200 × 20 mm) and covered with a Teflon sheet.
3. MDI and PP were mixed vigorously by mechanical stirring.
4. The mixture was poured into the die.
5. The die was covered with a Teflon-coated metal plate, and a pressure of 0.5 MPa was applied.

Table 1 Orthogonal array of Taguchi for the delamination (F_d)

Test	V, m min^{-1}	f, mm rpm^{-1}	L, mm	F_d, mm
1	6.28	0.03	10	1.16
2	6.28	0.03	15	1.19
3	6.28	0.03	20	1.20
4	6.28	0.05	10	1.11
5	6.28	0.05	15	1.16
6	6.28	0.05	20	1.18
7	6.28	0.07	10	1.18
8	6.28	0.07	15	1.21
9	6.28	0.07	20	1.24
10	12.56	0.03	10	1.19
11	12.56	0.03	15	1.22
12	12.56	0.03	20	1.26
13	12.56	0.05	10	1.17
14	12.56	0.05	15	1.19
15	12.56	0.05	20	1.23
16	12.56	0.07	10	1.21
17	12.56	0.07	15	1.22
18	12.56	0.07	20	1.25
19	18.84	0.03	10	1.11
20	18.84	0.03	15	1.16
21	18.84	0.03	20	1.18
22	18.84	0.05	10	1.10
23	18.84	0.05	15	1.14
24	18.84	0.05	20	1.15
25	18.84	0.07	10	1.16
26	18.84	0.07	15	1.18
27	18.84	0.07	20	1.21

6. PU rigid foam was removed from the die after curing for 20 min.
7. Woven glass fabric was laid-up on the PU foam core.
8. Polyester resin was laid up on each face of the glass fabric.
9. The specimens were cured in a hot press at a pressure of 0.5 MPa and 120 °C for 3 h.

2.3 Drilling Test

The experiments were carried out on hand lay-up sandwich specimens (200 × 200 × 20 mm thickness), using a WC-10%Co 2 mm diameter drill with a 118° point angle, a 22° helix angle, and a 26 mm flute length. A machine center with 10-kW spindle power and a maximum spindle speed of 6000 rpm was used to perform the experiments. The discs were squeezed in the jaw of the machining center via a system of clamps to make sure that vibrations and displacement did not occur. The experimental procedure was after Paulo et al. (Ref 13).

The drilling tests were conducted at three spindle surface speeds at the outer corner of the drill, namely 6.28, 12.56, and 18.84 m/min (corresponding to 1000, 2000, and 3000 rpm, respectively), at feed rates of 0.03, 0.05, and 0.07 mm/revolution (rev) for flute lengths of 10, 15, and 20 mm. The quality of holes was assessed using scanning electron microscopy (SEM).

2.4 Influence of Cutting Parameters on Delamination Factor

The delamination factor (F_d) is defined as the ratio of the maximum diameter (D, in μm) of the damage zone (measured using SEM) to the standard hole diameter (d, in μm) of the drill bits.

$$F_d = D/d \tag{Eq 1}$$

Table 2 Assignment of levels to the factors

Level	Cutting velocity V, m min^{-1}	Feed f, mm rev^{1}	Flute length L, mm
1	6.28	0.03	10
2	12.56	0.05	15
3	18.84	0.07	20

Table 3 Orthogonal array $L_{27}(3^{13})$ of Taguchi

$L_{27}(3^{13})$ test	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

Source: Ref 14

Table 1 shows the results of the delamination factor (F_d) for the drill tests, obtained by Eq 1 as a function of the cutting parameters.

2.5 Plan of Experiments Using Taguchi Technique

The drill tests were planned using the Taguchi technique with three factors and three levels (Table 2). The array chosen was an L_{27} (3^{13}), which has 27 rows corresponding to the number of tests with 26 degrees of freedom with 13 columns at three levels, as shown in Table 3. Factors and interactions are assigned to specific columns. The first column was assigned to the drilling velocity (V), the second to the feed rate (f), and the fifth column to the flank length (L), with the remaining columns assigned to their interactions. The delamination factor (F_d) was considered to be the response of the experiments. ANOVA of the experimental results was carried out to assess the significance of the factors and the interactions.

3. Results

The statistical treatment of the observed data was made in the following three phases:

Table 4 ANOVA delamination factors

Source	MF/I	DOF	SS (10^{-3})	MS (10^{-3})	F_{cal}	F_{tab}	P, %
V	MF	2	16.97	8.43	88.87		39.5
F	MF	2	10.29	5.14	54.21	$F_{0.05,\,2,\,8} = 4.46$	24.1
L	MF	2	14.66	7.33	77.23		34.0
$V \times F$	I	4	1.11	0.28	2.92		1.3
$F \times L$	I	4	0.12	0.03	0.29	$F_{0.05,\,4,\,8} = 3.84$	0.1
$V \times L$	I	4	0.20	0.05	0.54		0.2
Error		8	0.76	0.09	0.91		
Total		26	44.11	21.35	224.97		100

Note: V, velocity; F, feed rate; L, flank length; MF, main factor; I, interaction; P, percentage of contribution; DOF, degree of freedom; SS, sum of squares; MS, mean squares.

Table 5 Experimental plan for confirmation drilling tests and comparison with correlation results

V, m min^{-1}	f, mm rev^{1}	L, mm	F_d Experiment	Model	Error, %
6.28	0.03	10	1.162	1.149	1.2
12.56	0.05	15	1.192	1.170	1.8
18.84	0.07	20	1.216	1.193	1.9

- ANOVA and the effect of the factors and the interactions
- Correlation between the response and the experimental factors
- Confirmation tests

3.1 Analysis of Variance

The ANOVA of the experimental results is presented in Table 1. These results were used to investigate which of the cutting parameters significantly affected the quality of the hole, as defined by the delamination factor. Table 4 shows the results of the ANOVA with the delamination factors of the drilled holes for the sandwich structures. This analysis was carried out for a level of significance of 5%, i.e., for a level of confidence of 95%. The last column of Table 4 also indicates the percentage of contribution (P) of each factor on the total variation. It is observed that the drilling velocity (39.5%), feed rate (24.1%), and flute length (34.0%) had significant influence on the delamination factor, while the interactions of $V \times f$, $V \times L$, and $f \times V$ (1.3%, 0.1%, and 0.2%, respectively) were very small and had no significant effect.

3.1.1 Correlations. The correlations between drilling velocity, feed rate, and flute length, and response (i.e., delamination factor or diameter variation) were obtained by multiple linear regressions. The equation obtained was:

$$F_d = 1.093 - 0.002V + 0.688f + 0.0066L \qquad \text{(Eq 2)}$$

where F_d is the delamination factor, V is the cutting velocity in m/min, f is the feed rate in mm/rev, and L is flute length in mm.

3.1.2 Confirmation tests. Table 5 presents the drilling condition and delamination factor used in the drilling confirmation tests. The maximum error between the results predicted by the model and that of the confirmation tests was about 1.9%. Thus, Eq 2 correlates the delamination factor (F_d) in the sandwich structure with cutting velocity, feed rate, and drill length to a high degree.

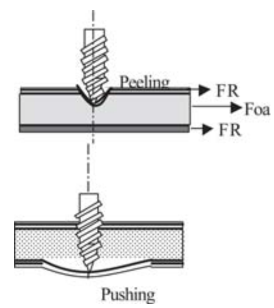

Fig. 1 Delamination damage mechanisms of sandwich drilling

4. Discussion

Experimental observations showed that delamination occurred at the entrance and at the exit. Two different mechanisms are responsible for this and for the quality of the hole both at the entrance and the exit. The two mechanisms are illustrated in Fig. 1. Delamination occurs as the drill tool pierces the surface of the sandwich during drilling. This mechanism is known as "peel-up." Similarly, as the tool approaches the exit side, the last ply (called the "back face") is under pressure from the drill tool and is prone to delamination. This is the "push-out" mechanism (Ref 14) where the drill pushes the uncut laminates in the downward direction and elastically deforms them. If the resulting strain at the top of the existing crack exceeds the critical value, crack propagation occurs. While the crack advances, the points at which the external force is applied will move.

More specifically, the cutting edges of the drill tool cut the face sheet of the sandwich initially. By moving forward, the tool tends to pull the abraded material away along the flute. The material spirals up before it is machined completely. This action introduces a peeling force upward that separates the upper face sheet from the uncut portion held by the downward-acting thrust force. The cutting force acting in the peripheral direction is the driving force for delamination. This generates a peeling force in the axial direction through the slope of the drill flute and is a function of the tool and work piece. Delamination caused by peel-up becomes progressively more severe as drilling proceeds, because the thickness resisting lamina bending becomes greater.

Generally, the edge quality at the hole entrance is better than at the hole exit, as shown in Fig. 2 A_{EN} and A_{EX}. The quality at the hole entrance also depends upon the speed, the feed rate, and the flute length of the drill. Figure $2B_{EN}$ shows the hole

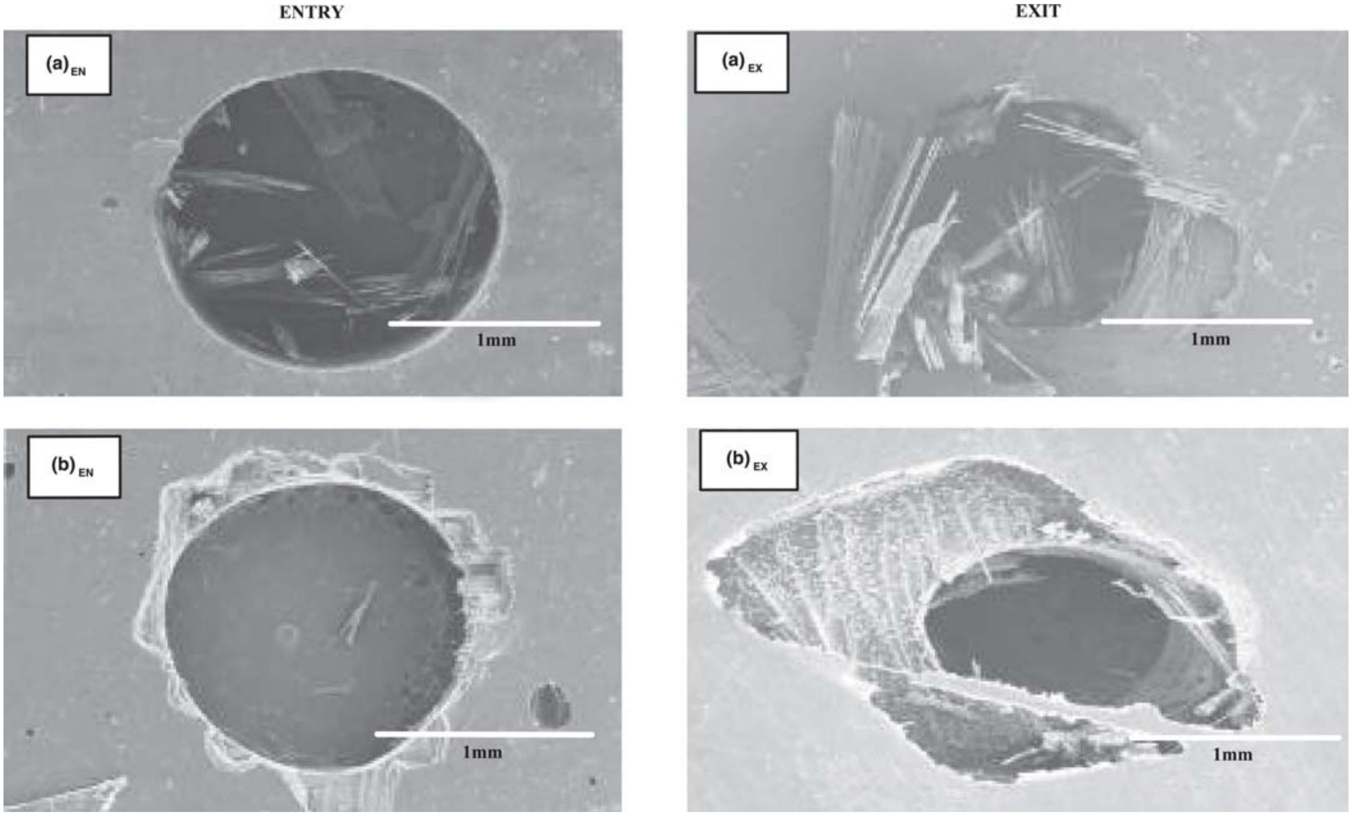

Fig. 2 Scanning electron micrographs of surface of drilled-hole by twist drill: (A_{EN}, A_{EX}) drill velocity 6.28 m/min, feed rate 0.03 mm/rev, and flute length 10 mm; (B_{EN}, B_{EX}) drill velocity 18.84 m/min, feed rate 0.7 mm/rev, and flute length 20 mm (EN and EX represent entry and exit of drilled hole, respectively)

entrance. Quality decreases at higher drill speeds because the drilling time decreases and the transverse vibration of the tool increases with an increase in speed, feed rate, and flute length. As the flute length increases the vibration amplitude increases. Hole clearance increases as a result of the enhanced vibration of the tool and the abrasives trapped in the gap. This effect is seen only at the hole entrance and not at the hole exit.

Mismatch between the elastic properties of the face sheet and the foam results in an in-plane tensile stress in the vicinity of the scratch that causes a crack to initiate and propagate through the specimen thickness. The crack arrests without significant growth beyond the initial scratch length caused by the foam. The result is a straight crack on the surface of the specimen rather than throughout the thickness of the sandwich structure.

Figure $2B_{EX}$ shows delamination and splintering at the hole exit are more serious with an increase in drill speed, when drilling is progressing toward the hole exit. The uncut thickness of the work piece becomes insufficient to resist the push-out of material. The sandwich structure under the drill tends to be drawn away from the laminate bond hole. As the drill approaches the end, the uncut thickness becomes smaller and the resistance to deformation decreases. At some point, the loading exceeds the interlaminar bond strength and delamination occurs. As the drill cuts downward, the uncut laminates under the tool are pushed and deformed elastically by the thrust force, as shown in the Fig. $2B_{EX}$. Pullout of fibers in bunches and strong adhesion of the matrix resin result in the brittle nature of the damage.

5. Conclusions

In this work, a series of experiments were conducted to study the effects of drilling velocity, feed rate, and flute length on drilling characteristics through a delamination factor. On the basis of experimental results, the following conclusions are made:

- Drilling velocity is the factor that has the greatest influence on the delamination factor (39.5%), followed by flute length (34%) and feed rate (24.1%).
- Interaction factors, i.e., drilling velocity/feed rate (1.3%), drilling velocity/flute length (0.1%), and feed rate/flute length (0.2), are of no physical significance to the interactions analyzed for the drilling operation.
- Error associated with the ANOVA (maximum 1.9% and minimum 1.2%) for the factors, and the coefficients of regression obtained from the multiple regression analysis (−0.002, 0.688, and 0.0066) show that satisfactory correlation was obtained.
- Delamination factor is mainly affected by drilling speed, flute length, and feed rate within the range of factors examined. The quality of the drilled hole deteriorates with increasing drilling velocity, flute length, and feed rates.

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