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ORIGINAL ARTICLE

Evaluation of the drilling-induced delamination of compound core-special drills using response surface methodology based on the Taguchi method

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Abstract The hole-making process in composite parts today is required to be more accurate and efficient, which can affect the in-service life and decrease manufacturing cost. Thus understanding the key factors affecting their qualities is of vital importance to develop effective machining strategies. To this end, this study proposes a model with response surface methodology (RSM) based on the Taguchi method to evaluate the influence of drilling parameters on delamination by compound core-special drills. The model with RSM includes three steps: (1) design and experiments, (2) response surface modeling through regression, and (3) optimization. A series of experiments were conducted to test the proposed model. It was found that the key factors affecting drilling-induced delamination include: cutting velocity ratio, feed rate, inner drill type, and inner drill diameter. Therefore, some experimental implications can be proposed accordingly.

Keywords Drilling · Delamination · Response surface methodology · Taguchi method · Compound core-special drills · Composite materials

1 Introduction

Composite materials are the most versatile of structural materials and are recognized for their superior mechanical properties, such as a high strength-to-weight ratio, high fracture toughness, and excellent corrosion resistance. However, the machinability and cutting behavior of composite materials differ from metals because they are anisotropic, inhomogeneous, and abrasive. Conventional methods for hole making on composite structures or parts involve the use of turning, drilling, milling, laser beams, water jets, and electrical discharge machining. Drilling still remains one of the most economical and efficient machining processes for hole making in the structural parts of composites owing to the need for riveting and fastening, which are widely used in the aerospace and automotive industries.

Delamination damage is one of the major defects during drilling. Several studies on drilling composites reported drilling quality strongly depends on tool geometry and drilling parameter [1–4]. Drilling-induced delamination leads to reduced structural strength and in-service life under fatigue loads, and a higher humidity and temperature environment. Miner and Mackey pointed out that new concepts of tooling different realms of cutting conditions to reduce drilling-induced damages of composites are needed [5, 6]. Hocheng and Tsao showed using a core drill bit could improve the quality of the hole finish in drilling [7, 8]. However, one disadvantage of this tool is the chip removal clog in drilling. Compound core-special drills can solve the problem of chip removal. They are composed of an outer drill (core drill) and an inner drill (twist drill, saw drill, or candlestick drill). A photograph of a compound core-special drill is shown in Fig. 1.

Response surface methodology (RSM) is a powerful technique for optimizing the process, which is frequently used to evaluate the results and efficiency of the operations [9–11]. On the other hand, many successful applications of the Taguchi methods have been reported to improve process and product performance, and reduce manufacturing costs [12, 13]. Therefore, RSM uses an experimental design such as the Taguchi method to examine the effects of various

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Fig. 1 Photograph of compound core-special drill

machining parameters on drilling-induced delamination of composite materials by compound core-special drills. Cutting velocity ratio, feed rate, stretch, inner drill type, and inner drill diameter as the key parameters affecting drilling-induced delamination of composite materials were studied in this evaluation.

2 Experimental setup and method

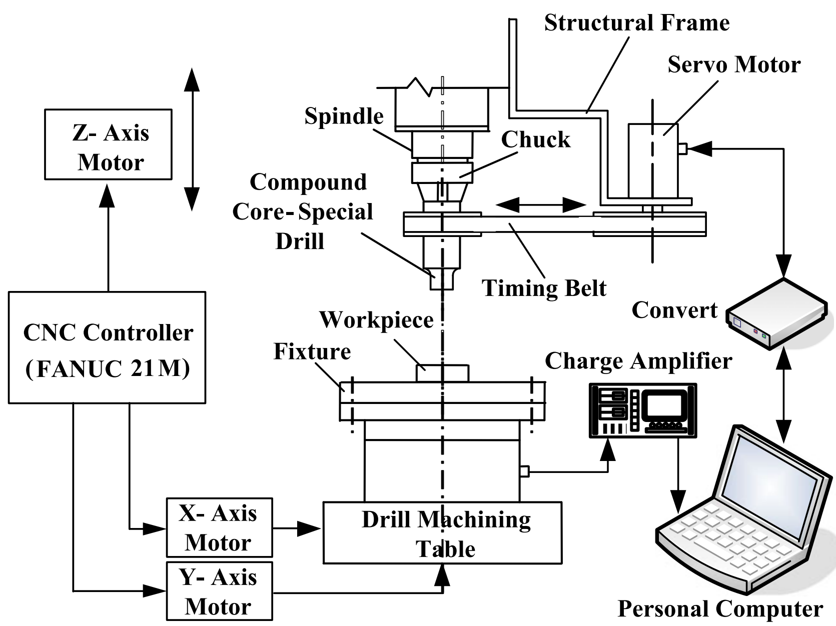
Composite laminates are being prepared in the laboratory from woven WFC200 fabric carbon fiber prepregs. The composite was a 16-ply ($[0°/90°]_{8S}$) laminate approximately 4 mm thick. A LEADWELL V30 vertical machining center with a 5.5-kW spindle drive was used in all drilling tests as shown in Fig. 2. The outer drill diameter and core tool thickness of the compound core-special drills are 10 and 1 mm, respectively, the end of the core tool plated with a #60 diamond grits, and its length is 12 mm. The internal parts of the compound core-special drills are the twist drill, saw drill, and candlestick drill, respectively. Tungsten carbide twist drills, saw drills, and candlestick drills of 5.6 and 6.8 mm diameter were used to obtain the entire drilling-induced delamination. Each test was replicated twice. All drilling tests were conducted coolant free at spindle speeds of 1,088, 1,224, and 1,360 rpm for outer drills, and spindle speeds of 1,000 and 1,214 rpm for inner drills, respectively.

The concept of the cutting velocity ratio (ξ) can easily resolve the problem of chip removal in drilling composite laminates. The equation of the cutting velocity ratio can be expressed as follows [14]:

$$\xi = \pm \frac{V_O}{V_I} = \pm \frac{n_O D_O}{n_I D_I} \qquad (1)$$

where V_O is the cutting velocity of outer drill in meters/minute, V_I is the cutting velocity of inner drill in meters/minute, n_O is the spindle speed of outer drill in revolutions per minute, n_I is the spindle speed of inner drill in revolutions per minute, D_O is the diameter of outer drill in millimeters, and D_I is the diameter of inner drill in millimeters. In this study, the rotational direction of the inner drill is always clockwise. When the rotational direction of inner drill is different from the rotational direction of outer drill, the cutting velocity ratio is negative. In addition, the stretch between outer drill and inner drill is also a significant factor to affect the delamination in drilling. The stretch is positive when the length of inner drill is longer than that of outer drill. The stretch, however, is equal to zero when the outer drill and the inner drill have the same length. Digital images of the drilling-induced delamination were produced from the carbon fiber-reinforced composite material sections obtained by ultrasonic C-scan. The ultrasonic C-scan equipment was an AIT-5112 unit (Automated Inspection Technologies Inc.). The

Fig. 2 Schematic diagram of experimental setup



specimen was placed between the sender and receiver and scanned at normal incidence in through-transmission mode by a focused broadband transducer (9.5 mm in diameter) with a center frequency of 5 MHz. The testing device consisted of a 0.025-mm resolution scanning bridge, an AIT-2230 ultrasonic pulser/receiver, and a digital oscilloscope used for radiofrequency echo signal acquisition. Commercial software (PhotoImpact 8.0) was used to extract the ultrasonic C-scan image data during scanning for measuring the drilling-induced delamination.

An $L_{18}(6\times3^6)$ orthogonal array and signal-to-noise (*S*/*N*) ratio are used to realize the degree of influence on drilling-induced delamination for machining parameters (cutting velocity ratio, feed rate, stretch, inner drill type, and inner drill diameter) using compound core-special drills in drilling composite laminates. Table 1 indicates the drilling test parameters and levels. In this investigation, the drilling-induced delamination is used as a quality character factor to realize the effect of the machining parameters (particularly for cutting velocity ratio and stretch) to get the smaller the better characteristic. The *S*/*N* ratio of the smaller the better characteristic (η) can be expressed as follows:

$$\eta = -10\log\frac{1}{k}\sum_{j=1}^{k}{y_j}^2 \qquad (2)$$

where k is the number of repetitions of the experiment and y_j is the average measured value of experimental data j.

RSM usually contains three steps: (1) design and experiments, (2) response surface modeling through regression, and (3) optimization. The main objective of RSM is to determine the optimal operational conditions of the process or to determine a region that meets the operating specifications [15]. When the response data are obtained from the test work, a regression analysis is carried out to determine the coefficients of the response model, their standard errors, and significance. In general, a second-order polynomial response surface mathematical model is considered to analyze the parametric influences on the various response criteria. The second-order model helps understand the second-order effect of each variable separately and the two-way interaction amongst these variables combined. This second-order mathematical model can be represented as follows:

$$Y = b_o + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n} b_{ii} X_{ii}^2 + \sum_{i<j} b_{ij} X_i X_j + \varepsilon \qquad (3)$$

where Y is the corresponding response; X_i is the input variables; ${X_{ii}}^2$ and X_iX_j are the squares and interaction terms of these input variables; b_o, b_i, b_{ij}, and b_{ii} are the regression coefficients of parameters; and ε is the experimental error.

3 Results and discussion

3.1 Analysis of variance and confirmatory test

A series of experiments were carried out as shown in Table 2. Table 3 shows the analysis of variance (ANOVA) results for delamination in drilling composite laminates. In Table 3, the most important variables affecting drilling-induced delamination are feed rate (P=39.6%), cutting velocity ratio (P=26.1%), inner drill diameter (P=21.0%), and the inner drill type (P=6.8%). The feed rate, cutting velocity ratio, inner drill diameter, and the inner drill type show the statistical and physical significance in drilling carbon fiber-reinforced plastics composite laminates by core-special drills [10, 14, 16–18]. However, the stretch is insignificant in the drilling of composite laminates. As shown in Table 3, the optimum conditions were identified within the selected tested range, such as A_3, B_2, C_3, D_3, and E_1 (i.e., cutting velocity ratio=−1.6, feed rate=15 mm/min, stretch=0.5 mm, inner drill type=candlestick drill, and inner drill diameter=5.6 mm). Once the optimal design parameter level is selected, the final step verifies the quality characteristic improvement using the optimal design parameter level. Table 4 shows the experimental result of confirmatory test for drilling-induced delamination of compound core-special drill. A comparison of the optimal design parameter level ($A_3B_2C_3D_3E_1$) with the initial process parameters ($A_3B_2C_3D_2E_1$) shows drilling-induced delamination decreases from 24.69 to 23.85 pixels.

Table 1 Drilling test parameters and levels

Symbol	Control factor	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
X_1	Cutting velocity ratio	−2.0	−1.8	−1.6	1.6	1.8	2.0
X_2	Feed rate (mm/min)	10	15	20			
X_3	Stretch (mm)	−0.5	0	0.5			
X_4	Inner drill type	Twist	Saw	Candlestick			
X_5	Inner drill diameter (mm)	5.6	6.8				

Table 2 $L_{18}(6\times3^6)$ orthogonal array and experimental results for drilling-induced delamination and their corresponding S/N ratio

Trial	Factor					Delamination (pixel), observed	Delamination (pixel), predicted	S/N ratio (db), η
	X_1	X_2	X_3	X_4	X_5			
1	−2.0	10	−0.5	34.9	5.6	27.74	27.44	−28.9
2	−2.0	15	0	28.6	6.8	28.69	29.26	−29.2
3	−2.0	20	0.5	25.1	5.6	27.87	28.26	−28.9
4	−1.8	10	−0.5	28.6	6.8	33.95	33.34	−30.6
5	−1.8	15	0	25.1	5.6	26.06	25.42	−28.3
6	−1.8	20	0.5	34.9	5.6	30.75	30.35	−29.8
7	−1.6	10	0	34.9	5.6	26.04	26.33	−28.3
8	−1.6	15	0.5	28.6	5.6	24.69	24.99	−27.9
9	−1.6	20	−0.5	25.1	6.8	29.02	28.64	−29.3
10	1.6	10	0.5	25.1	6.8	30.18	30.19	−29.6
11	1.6	15	−0.5	34.9	5.6	25.38	25.57	−28.1
12	1.6	20	0	28.6	5.6	32.58	30.94	−30.3
13	1.8	10	0	25.1	5.6	28.29	29.2	−29.0
14	1.8	15	0.5	34.9	6.8	27.85	27.66	−28.9
15	1.8	20	−0.5	28.6	5.6	29.76	31.57	−29.5
16	2.0	10	0.5	28.6	5.6	29.58	28.65	−29.4
17	2.0	15	−0.5	25.1	5.6	27.95	27.19	−28.9
18	2.0	20	0	34.9	6.8	33.76	33.62	−30.6

3.2 Fitted regression models

Further, the inner drill type is not a quantitative parameter. Several researchers have shown the extent of drilling-induced delamination is correlated with the thrust force [2, 7, 19]. Hocheng and Tsao reported the critical thrust forces of the twist drill, saw drill, and candlestick drill were 34.9, 28.6, and 25.1 N, respectively, in drilling composite materials [7]. However, the critical thrust force of the saw drill is larger than the candlestick drill due to the more complicated tool geometry and shear force contributing to the mode III interlaminar fracture. From the experimental design and results in Table 2, the second-order response functions representing delamination (Y_D) in drilling composite laminates can be expressed as a function of four drilling parameters, namely the cutting velocity ratio (X_1), feed rate (X_2), inner drill type (X_4), and inner drill diameter (X_5). The relationship between responses (delamination) and drilling parameters were obtained as follows:

$$\begin{aligned} Y_D = {} & -135636.4 + 2.64X_1 - 4.14X_2 - 1.45X_4 + 44190.25X_5 \\ & +7.12\times10^{-1}X_1^2 + 1.35\times10^{-1}X_2^2 - 3.05\times10^{-3}X_4^2 - 3563.65X_5^2 \\ & +9.34\times10^{-2}X_1X_2 - 8.38\times10^{-3}X_1X_4 - 6.26\times10^{-1}X_1X_5 \\ & +5.43\times10^{-2}X_2X_4 - 0.23X_2X_5 + 0.14X_4X_5 \quad (\mathrm{mm}) \end{aligned} \tag{4}$$

Table 3 ANOVA for drilling-induced delamination

Factor	Level (*S/N* ratio)						Degree of freedom	Sum of squares	Variance	Percentage of contribution, *P* (%)
	1	2	3	4	5	6				
A	−29.0	−29.6	−28.5	−29.3	−29.1	−29.6	5	2.76	0.55	26.1
B	−29.3	−28.5	−29.7				2	4.20	2.10	39.6
C	−29.2	−29.3	−29.1				2	0.13	0.06	1.2
D	−29.1	−29.5	−29.0				2	0.72	0.36	6.8
E	−28.9	−29.7					1	2.23	2.23	21.0
Error							5	0.56	0.11	5.3
Pooled error							(7)	(0.69)	(0.10)	(6.5)
Total							17	10.60		100

Table 4 Experimental result of confirmatory test for drilling-induced delamination of compound core-special drill

Level	Currently drilling condition $A_3B_2C_3D_2E_1$	Optimum drilling condition $A_3B_2C_3D_3E_1$
Drilling-induced delamination (pixel)	24.69	23.85
ABS variation (%)	3.52	

The response factors at any regime in the interval of selected experiment design can be calculated from Eq. 4. The predicted values obtained using the model equation is shown in Fig. 3. Clearly, the predicted values match the experimental values reasonably well, with R^2 of 0.917 for drilling-induced delamination of composite laminates.

3.3 Effect of drilling variables on drilling-induced delamination

The response surface plots demonstrate the effect of different variables on drilling-induced delamination as shown in Fig. 4. Figure 4a shows the effect of the cutting velocity ratio and feed rate on drilling-induced delamination. Note that a lower inverse cutting velocity ratio and medium feed rate have a minor effect on drilling-induced delamination. However, it is worth noting that larger drilling-induced delamination is obtained at the larger positive cutting velocity ratio and larger feed rate. Generally, the inverse direction of cutting velocity ratio can reduce the threat of drilling-induced delamination at the exit plane of the drill and the risk of chip clogging within compound core-special drills compared to positive direction of cutting velocity ratio [14]. Decreasing the negative cutting velocity ratio leads to a decrease in the contact number between tool and workpiece, and consequently decreases the drilling-induced delamination at the exit plane. Figure 4b presents the effect of the cutting velocity ratio and inner drill type on drilling-induced delamination. It can be seen drilling-induced delamination depends more on the cutting velocity ratio rather than on inner drill type. Note, lower drilling-induced delamination is obtained at the lower negative cutting velocity ratio and using the candlestick drill type. Special drill bits (saw drill and candlestick drill) can acquire better machining quality in drilling composite laminates due to the special drill bits utilize the peripheral distribution of thrust for drilling the composite laminates [7]. However, the tool wear for the cutting edges of saw drill is more than the candlestick drill in drilling composites because cutting edges of saw drill are very sharp. Figure 4c indicates the effect of the cutting velocity ratio and inner drill diameter on drilling-induced delamination. A minor drilling-induced delamination is obtained with a lower negative cutting velocity ratio and lower inner drill diameter. A greater inner drill diameter generates a higher thrust force, which increases drilling-induced delamination. The chips produced by the larger inner drill diameter clink easily with the inner space of compound core-special drill during drilling. Figure 4d reports the effect of feed rate and inner drill type on drilling-induced delamination. The general form of the three-dimensional relationship is similar to Fig. 4b. Figure 4e shows the effect of the feed rate and inner drill diameter on drilling-induced delamination. Minimum drilling-induced delamination is obtained with a medium level feed rate and lower inner drill diameter. Figure 4e clearly shows the middle level of the feed rate is a good condition for achieving lower drilling-induced delamination. However, a higher spindle speed helps remove excess heat rapidly and also eject the chips produced during cutting [10]. Figure 4f shows the effect of the inner drill type and inner drill diameter on drilling-induced delamination. Drilling-induced delamination depends more on the inner drill diameter rather than on the inner drill type. The lower drilling-induced delamination is obtained at a lower inner drill diameter using a candlestick drill. A similar drilling-induced delamination trend is also observed due to the interaction effect of the cutting velocity ratio and inner drill type, as shown in Fig. 4b.

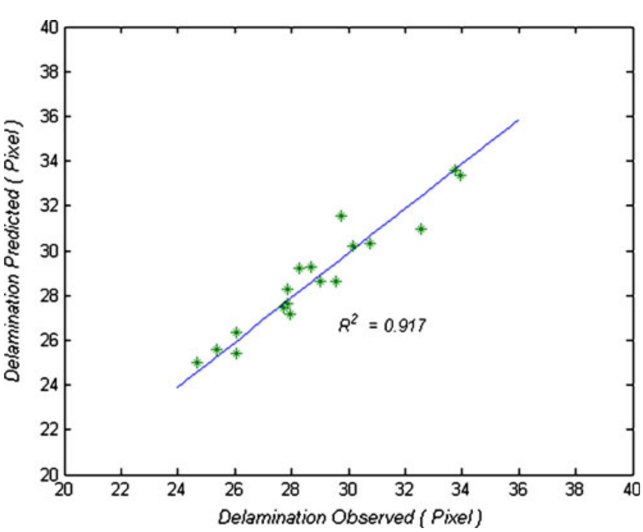
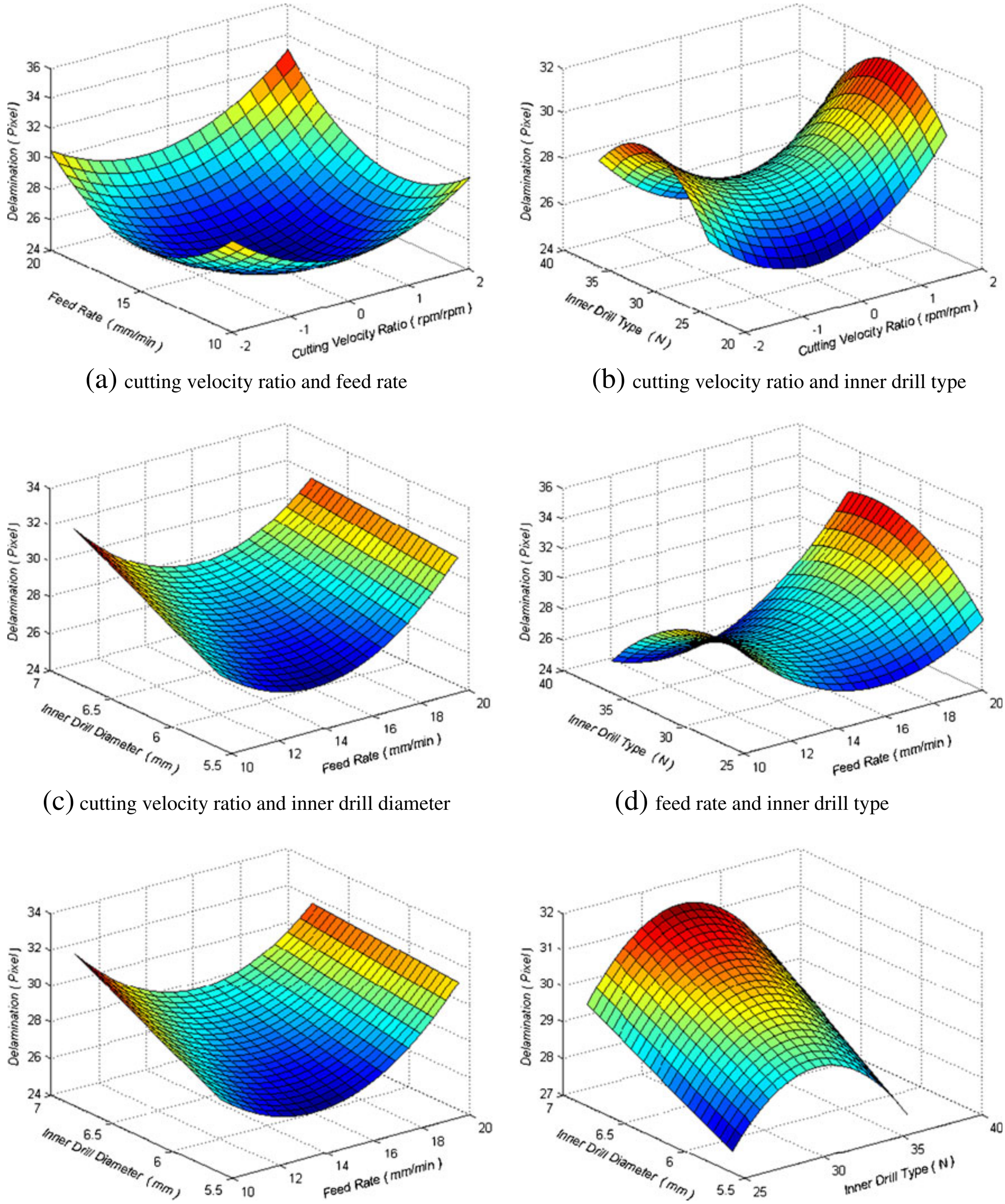


Fig. 3 Relation between the experimental and predicted delamination of drilling composite laminates using Eq. 4

4 Summary and conclusion

The application of the RSM based on the Taguchi method for modeling the influence of four major machining



(a) cutting velocity ratio and feed rate

(b) cutting velocity ratio and inner drill type

(c) cutting velocity ratio and inner drill diameter

(d) feed rate and inner drill type

(e) feed rate and inner drill diameter

(f) inner drill type and inner drill diameter

Fig. 4 a–**f** Response surface plots showing the effect of two variables on drilling-induced delamination

variables (namely cutting velocity ratio, feed rate, inner drill type, and inner drill diameter) on the performance of drilling composite laminates has been discussed. The predicted values match the experimental values reasonably well, with R^2 of 0.917 for drilling-induced delamination. In the findings from the ANOVA, however, the most important variables affecting drilling-induced delamination are feed rate (P=39.6%), cutting velocity ratio (P=26.1%), inner drill diameter (P=21.0%), and the inner drill type (P=6.8%). The optimum condition for delamination in drilling composite laminates by compound core-special drills was obtained at −1.6 cutting velocity ratio (A_3), 15 mm/min feed rate (B_2), 0.5 mm stretch (C_3), a candlestick drill (inner drill type, D_3), and 5.6 mm inner drill diameter (E_1) settings. The validation experiments show an improved drilling-induced delamination of 3.52% when the Taguchi method is used. Besides, lower inverse cutting velocity ratio, medium feed rate, lower inner drill diameter, and a candlestick drill (inner drill type) produce a lower drilling-induced delamination.

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