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International Journal of Machine Tools & Manufacture 44 (2004) 1085–1090
INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE DESIGN, RESEARCH AND APPLICATION
www.elsevier.com/locate/ijmactool

Taguchi analysis of delamination associated with various drill bits in drilling of composite material

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Received 6 October 2003; received in revised form 10 February 2004; accepted 26 February 2004

Abstract

This paper presents a prediction and evaluation of delamination factor in use of twist drill, candle stick drill and saw drill. The approach is based on Taguchi's method and the analysis of variance (ANOVA). An ultrasonic C-Scan to examine the delamination of carbon fiber-reinforced plastic (CFRP) laminate is used in this paper. The experiments were conducted to study the delamination factor under various cutting conditions. The experimental results indicate that the feed rate and the drill diameter are recognized to make the most significant contribution to the overall performance. The objective was to establish a correlation between feed rate, spindle speed and drill diameter with the induced delamination in a CFRP laminate. The correlation was obtained by multi-variable linear regression and compared with the experimental results.

Keywords: Candle stick drill; Saw drill; Delamination factor; Taguchi method

1. Introduction

The advantage of composite materials over conventional materials stem largely from their higher specific strength, stiffness and fatigue characteristics, which enables structural design to be more versatile. Due to the inhomogeneous and anisotropic nature of composite materials, their machining behavior differs in many respects from metal machining. In recent years, customer requirements have put greater emphasis on the product development with new challenges to manufactures, such as machining techniques. Machining of composite materials requires the need for better understanding of cutting processes regarding accuracy and efficiency. Though near-net shape processes have gained a lot of attention, more intricate products need secondary machining for the required accuracy. Drilling is the most frequently employed operation of secondary machining for fiber-reinforced materials. Inspection of carbon fiber-based composites by optical methods is difficult. With increasing application of composite structures, visual inspection and assessment techniques of interface delamination are becoming vital. In general, ultrasonic C-Scan has been widely employed for this purpose.

The mechanics of drilling composite materials has been studied along with the quality of the hole and the effects of tool geometry and tool material [1,2]. Chen [2] proposed a delamination factor to characterize the delamination in drilling carbon fiber-reinforced plastic (CFRP). The fibrils or fuzz caused by conventional tools, which cut the holes in the center and force chips against walls, can be significantly reduced. The influence of tool wear and the resulting increase of thrust were discussed [3–5]. Miner [6] and Mackey [7] studied the complexities of machining of the two-phase composite materials and concluded that not only new concepts of tooling but also different realms of cutting conditions are needed. Koplev [8] was the first declared that chip formation in composite removal is a process of serial material fractures. Sakuma and Seto [9] point out that there is a strong correlation between the rapid rise of the cutting temperature and the existence of the critical speed causing drastic tool wear. Lin and Chen

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0890-6955/$ - see front matter
doi:10.1016/j.ijmachtools.2004.02.019

[10] studied the effects of increasing cutting speed on drilling of CFRP. Sakuma et al. [11] also compared the different tool wear in cutting CFRP and GFRP based on their physical and mechanical properties. Koenig et al. [12,13] investigated the effect of processing variables on drilling damage. Dharan and Won [14] developed an intelligent machining system to determine the key process parameters for various cutting conditions and design of a new machine tool. A general overview of the various possibilities for machining composites can be found [15].

Drilling-induced delamination occurs both at the entrance and the exit planes of the workpiece. Investigators have studied analytically and experimentally cases in which delamination in drilling have been correlated to the thrust force during exit of the drill. A significant portion of the thrust force is due to the chisel edge, as has been shown in [16,17]. Increasing the chisel edge length results in an increase in thrust force. The candle stick drill and saw drill have a smaller center than the twist drill; thus, a smaller extent of the last laminate is subjected to a bending force. Experiments indicate that there exists a critical thrust force below which no delamination occurs. Above that level, matrix cracks are generated by interface delamination growing from the crack tips. The first analytical model to determine the critical thrust force of the twist drill was formulated by Hocheng and Dharan [18]. They employed linear elastic fracture mechanics and solved for the critical thrust force that relates the delamination of composite laminates to drilling parameters and composite material properties. Hocheng and Tsao [19–21] developed a series analytical model of special drills (candle stick drill, saw drill, core drill and step drill) for correlating the thrust force with the onset of delamination.

Enemuoh et al. [22] developed an approach combining Taguchi's method and multi-objective optimization criterion to obtain the optimum drilling conditions for delamination-free drilling in composite laminates. Davim and Reis [23] also presented a similar approach using Taguchi's method and the analysis of variance (ANOVA) to establish a correlation between cutting velocity and feed rate with the delamination in a CFRP laminate.

All the above work contributes to the practice of twist drill, while the use of various drill bits and the characterization of their machinability were rarely discussed in design experiments. This paper presents a prediction and comparison of delamination factors of twist drill, candle stick drill and saw drill.

2. Experimental procedure

2.1. Specimens and drilling tests

The composite materials for drilling were fabricated from the woven WFC200 fabric carbon fiber/epoxy matrix using autoclave molding. The stacking sequence of the laminates was $[0/90]_{12S}$. The CFRP laminates were approximately 5 mm thick consisting of 24 plies and had a 55% cured fiber volume fraction. Specimens of size 60 mm × 60 mm were cut on a water-cooled diamond table saw. Drilling tests were conducted on a LEADWELL MCV-610AP vertical machining center as shown in Fig. 1. A proper fixture with a center hole of 24 mm diameter was used to support the laminate, which is firmly held on top of the dynamometer. All three drill bits used were high speed steel of 30° helix angle and 10 mm diameter as shown in Fig. 2.

2.2. Taguchi method

Taguchi methods which combine the experiment design theory and the quality loss function concept have been applied to the robust design of products and process and have solved some confusing problems in manufacturing. In order to observe the influence degree of control factors (feed rate, spindle speed and drill diameter) in drilling, three factors, each at three levels, are considered. Namely, a L_9 (3^4) orthogonal array was employed. Table 1 indicates the drilling test parameters.

2.3. Ultrasonic C-Scan

Delamination is among the most serious concerns during drilling of fiber-reinforced composite materials, while the evaluation of the drilling-induced delamination damage in the material is rather difficult, Particularly for the carbon fiber-based composites, as their colour makes visual inspection difficult. Visualization and assessment of the internal delamination is a difficult and challenging task. Interrogation of the composite materials to obtain comprehensive knowledge of the size, shape and location of delamination nondestructively is highly desirable. An ultrasonic C-Scan using the sound energy at frequencies above 20 kHz to

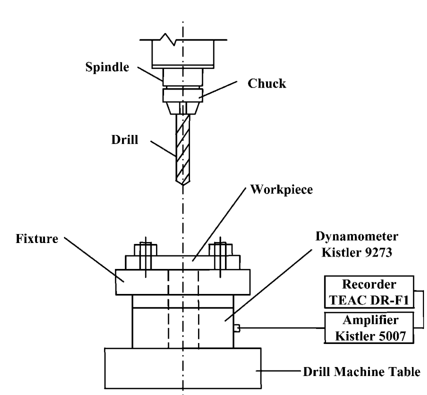

Fig. 1. Schematic of drilling set-up.

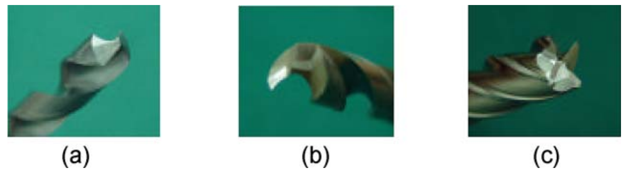

Fig. 2. Photograph of three different type drills. (a) Twist drill; (b) candle stick drill; (c) saw drill.

Table 1
Levels of drill test factors

Sample	Control factor	Level 1	Level 2	Level 3
A	Feed rate (mm/rev)	0.01	0.02	0.03
B	Spindle speed (rpm)	800	1000	1200
C	Drill diameter (mm)	6	8	10

detect the defect of specimen is presented in the current paper. The tested specimens immersed in water were scanned at normal incidence in pulse-echo mode by means of a focused broadband transducer (3.2 mm diameter, 18 mm focal length) with a center frequency of 5 MHz. The testing device consists of a 0.025 mm resolution scanning bridge, a JSR-DPR002 ultrasonic pulser/receiver and a digital oscilloscope used for radio frequency echo signal acquisition. The same gate location and width were selected for all the post-processing of data for reconstruction of delamination. The schematic of ultrasonic C-Scan is shown in Fig. 3.

3. Computation of delamination factor

The imaging process converts the useful ultrasonic image data into a gray level array. These data are used to determine the delamination factor. A picture consisting of 125 × 125 resolution (pixels) was obtained from each scanning. Each delamination image is represented by an array of gray scale values (0–255) corresponding to differences in laminates density. To obtain the useful image, the pixel value of the center drilled hole is set to 0 (black) when it is more than the threshold value; the delamination zone is meanwhile set to 255 (white). The proper threshold values were determined by examining the histogram of array values and verified by the original and binary images, as shown in Fig. 4. Based on the binary images, the drilling delamination factor is determined by the ratio of the maximum diameter (D_{max}) of the delamination zone to the hole diameter (D). The scheme is shown in Fig. 5. The value of delamination factor (F_d) can be expressed as follows

$$F_d = \frac{D_{max}}{D} \tag{1}$$

where the unit of D_{max} and D is the pixel.

4. Experimental results

4.1. Analysis of variance

Table 2 shows the results of the delamination factor of three drilling sets obtained by Eq. (1). Tables 3–5 illustrate the results of the ANOVA with the delamination factor in CFRP laminate. In Table 3, the most important variable affecting the delamination factor is the feed rate ($P = 80.9\%$). The feed rate shows statistical and physical significance in drilling CFRP laminate by twist drill. From the analysis of Table 4, drill diameter ($P = 60.6\%$) has statistical and physical signifi-

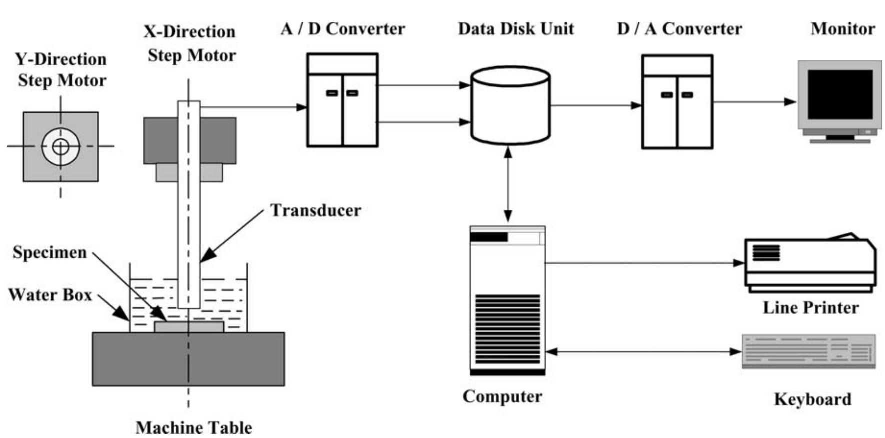

Fig. 3. Schematic of ultrasonic C-Scan.

(a) (b) (c)

Fig. 4. Ultrasonic C-Scan showing the extent of drilling-induced delamination for different drills ($f = 0.01$ mm/rev, $N = 1000$ rpm and $d = 8$ mm). (a) Twist drill; (b) candle stick drill; (c) saw drill.

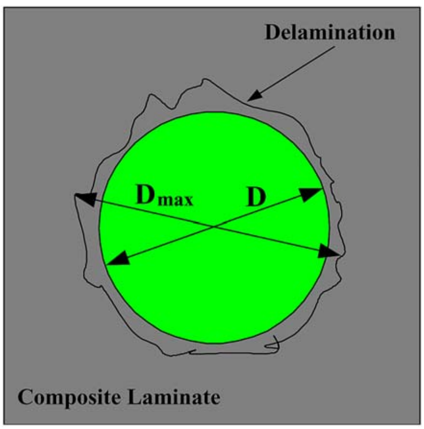

Fig. 5. Scheme of the delamination factor with ultrasonic C-Scan.

Table 2
L_9 (3^4) orthogonal array and values of delamination factor (F_d)

Trial	A	B	C	Delamination factor (F_d)		
	1	2	3	Twist drill	Candle stick drill	Saw drill
1	0.01	800	6	1.667	1.396	1.417
2	0.01	1000	8	1.531	1.375	1.313
3	0.01	1200	10	1.475	1.350	1.350
4	0.02	800	8	1.375	1.344	1.328
5	0.02	1000	10	1.375	1.300	1.288
6	0.02	1200	6	1.333	1.396	1.396
7	0.03	800	10	1.313	1.313	1.288
8	0.03	1000	6	1.375	1.375	1.292
9	0.03	1200	8	1.328	1.297	1.297

Table 3
ANOVA for the delamination factor (F_d) of twist drill

Factor	Level (S/N)			DF	SS	V	$F = 5\%$	P (%)
	1	2	3					
A	−3.84	−2.68	−2.53	2	3.08	1.54	12.6	80.9
B	−3.19	−3.08	−2.78	2	0.27	0.14		
C	−3.23	−2.98	−2.83	2	0.24	0.12		
Error				2	0.21	0.11		
PE				6	0.72	0.12		19.1
Total				8	3.80			100

DF, degree of freedom; SS, sum of squares; P, percentage of contribution; PE, pooled error.

Table 4
ANOVA for the delamination factor (F_d) of candle stick drill

Factor	Level (S/N)			DF	SS	V	$F = 5\%$	P (%)
	1	2	3					
A	−2.76	−2.58	−2.46	2	0.13	0.065	3.76	25.9
B	−2.61	−2.60	−2.59	2	0	0		
C	−2.85	−2.53	−2.42	2	0.31	0.155	8.86	60.6
Error				2	0.07	0.035		13.4
PE				4	0.07	0.018		13.5
Total				8	0.51			100

DF, degree of freedom; SS, sum of squares; P, percentage of contribution; PE, pooled error.

Table 5
ANOVA for the delamination factor (F_d) of saw drill

Factor	Level (S/N)			DF	SS	V	$F = 5\%$	P (%)
	1	2	3					
A	−2.66	−2.52	−2.23	2	0.30	0.15	30.0	38.6
B	−2.56	−2.26	−2.59	2	0.20	0.10	20.0	25.5
C	−2.72	−2.36	−2.33	2	0.27	0.135	27.0	35.0
Error				2	0.01	0.005		0.9
PE				2	0.01	0.005		
Total				8	0.78			100

DF, degree of freedom; SS, sum of squares; P, percentage of contribution; PE, pooled error.

cance on the delamination factor obtained. The factor of feed rate ($P = 25.9\%$) does not present the statistical significance on the delamination factor. In Table 5, feed rate, spindle speed and drill diameter have statistical and physical significance on the delamination factor obtained. From the analysis above, the feed rate and drill diameter are seen to make the largest contribution to the overall performance. Hocheng and Tsao [19] proposed the models to explain the advantage of distributing the thrust force toward the drill periphery, as shown in use of the saw drill and the candle stick drill.

4.2. Correlation between delamination factor and cutting parameters

In use of the multi-variable linear regression analysis, the correlation between delamination factor and cutting parameters in drilling CFRP was obtained. The equations can be express as follows:

(A) Twist drill

$$F_d = 1.961 - 10.955f - 1.81 \times 10^{-4}N - 1.77 \times 10^{-2}d \qquad R^2 = 0.796 \tag{2}$$

(B) Candle stick drill

$$F_d = 1.539 - 2.274f - 7.81 \times 10^{-6}N - 1.7 \times 10^{-2}d \qquad R^2 = 0.824 \tag{3}$$

Table 6
Cutting conditions in confirmation tests

Type of drill	Test	f (mm/rev)	N (rpm)	d (mm)
Twist drill	1	0.025	1100	6.8
	2	0.015	900	8.5
Candle stick drill	3	0.025	1100	6.8
	4	0.015	900	8.5
Saw drill	5	0.025	950	6
	6	0.015	850	8

Table 7
Experimental confirmation and comparison with model

Test	Delamination factor (F_d)		
	Experimental values	Model Eqs. (2) and (4)	Error (%)
1	1.324	1.368	3.3
2	1.382	1.484	7.3
3	1.287	1.358	5.5
4	1.324	1.353	2.2
5	1.354	1.342	0.9
6	1.359	1.345	1.0

(C) Saw drill

$$F_d = 1.508 - 3.385f + 8.681 \times 10^{-6}N - 1.49 \times 10^{-2}d \qquad R^2 = 0.654 \tag{4}$$

where f is the feed rate in mm/rev, N is the spindle speed in rpm and d is the drill diameter in mm.

4.3. Confirmation test

The cutting conditions used in the confirmation tests are shown in Table 6. Table 7 indicates the comparison between the foreseen values by the models developed in this study and the experimental results of delamination factor. The obtained results of both experimental results and model (Eqs. (2)–(4)) show the same deviation (within 8%). Hence, Eqs. (2)–(4) are demonstrated a feasible and an effective way for the evaluation of drilling-induced delamination factor.

5. Conclusions

An experimental approach to the evaluation of delamination caused by various drill bits using design experiments was proposed in this study. The results are summarized as follows:

1. The feed rate and drill diameter are seen to make the largest contribution to the overall performance.
2. The candle stick drill and saw drill cause a smaller delamination factor than twist drill. The results agree with the industrial experience.
3. The confirmation tests demonstrated a feasible and an effective method for the evaluation of drilling-induced delamination factor (errors within 8%) in drilling of composite material.

Acknowledgements

This work is supported by National Science Council, Taiwan, ROC, under contract NSC 92-2815-C-233-001-E.

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