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Evaluation of Novel Approach on Delamination Factor after Drilling Composite Laminates

Chung-Chen Tsao[1,a], Kei-Lin Kuo[2,b] and I-Chien Hsu[3,c]

[1]Department of Automation Engineering, Tahua Institute of Technology, Taiwan

[2]Department of Vehicle Engineering, National Taipei University of Technology, Taiwan

[3]Department of Electrical Engineering, Tahua Institute of Technology, Taiwan

[a]aetcc@thit.edu.tw, [b]klkuo@ntut.edu.tw, [c]ichien@thit.edu.tw

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Abstract. Drilling is the most economic and convenient operation of secondary machining for hole making of fiber-reinforced materials owing to the need for structure joining. Delamination is commonly recognized as a major defect after drilling composite materials. In general, the delamination is an irregular shape and size, containing long and fine breaks and cracks at the exit of the drilled hole, especially in the drilling of carbon fiber-reinforced plastic (CFRP). The conventional delamination factor (F_a) is not appropriated to characterize the damage area because the shape of the delamination after drilled CFRP is not a regular representation of the damage magnitude. In this paper, a novel approach of the equivalent delamination factor (F_{ed}) is proposed and compared with the adjusted delamination factor (F_{da}) and the conventional delamination factor (F_a). The experimental results show the F_{ed} obtained is considered suitable for characterizing delamination at the exit of a hole after drilling composite materials.

Introduction

Carbon-fiber reinforced composites have gained much attention for their superior mechanical properties and are attractive for use in aerospace, defense and transportation applications. However, these materials possess peculiar characteristics governing their behavior during machining. The mechanism of machining composite materials has been identified as fundamentally different from that of homogeneous metal removal [1]. Based on experimental observations, little plastic deformation of composite materials occurs during cutting, and the fracture resistance is ten to one hundred times lower than that of common steels. Drilling is the most economic and convenient operation of secondary machining for hole making of fiber-reinforced materials owing to the need for structure joining. Various cutting tools are available for hole making, but the twist drill with two cutting edges on its working end is by far the most common. However, the efficiency of the cutting action varies, being the most efficient at the outer diameter of the twist drill. The delamination damage caused by the cutting edges of twist drill bits is one of the major concerns during drilling. Many references of the drilling of fiber-reinforced plastics state the quality of the cut surfaces strongly depends on the drilling parameters [1, 2]. Kobayashi stated the larger the feeding load, the more serious the cracking around the exit edge of the hole [3]. On the other hand, damage development and detection, new tooling design, and the influences of cutting conditions in drilling composite materials have been studied [4-9]. Several non-traditional machining processes, such as laser-beam drilling, water-jet drilling (with or without abrasive additive), ultrasonic drilling, electro discharge machining (EDM), have been reported as alternatives. Nevertheless, conventional drilling still continues to be used widely for practical purposes.

In general, delamination occurs both at the entrance and the exit planes of the workpiece after drilling. However, the quality control and evaluation of drilling-induced delamination during the drilling of fiber-reinforced composite materials is rather difficult. Many investigators reported X-ray, optical microscope, ultrasonic C-scan and digital photograph have been commonly used to acquire

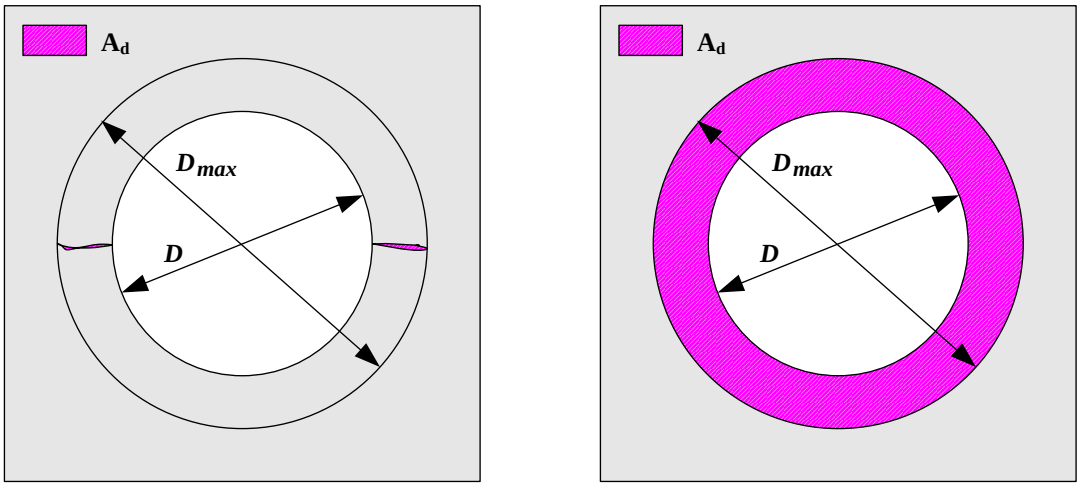
the size, shape and location of delamination on the composite laminates. Tsao and Hocheng present a comparative study on computerized tomography and ultrasonic C-scan evaluation techniques for characterizing the drilled damage in carbon-fibre-reinforced composites. They concluded that visual inspection is demonstrated as a feasible and an effective tool for the evaluation of drilling-induced delamination [10]. Chen first proposed the concept of the delamination factor (i.e. the ratio of the maximum diameter D_{max} in the damage zone to the hole diameter D), namely the equivalent delamination factor (F_a), to easily analyze and compare the delamination degree in the drilling CFRP composite laminates [11]. The equation of conventional delamination factor can be expressed as follows

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

Advanced technology of digital image processing to measure drilling-induced delamination has been widely used because it emphasizes the improvement of process efficiency, stability of image quality and cost-saving. Davim et al. proposed the adjusted delamination factor (F_{da}) to evaluate the delamination zone by digital image processing after drilling composite laminates [12]. The advantage of the measurement technology is it incorporates a novel approach of area function. The F_{da} gave better results of measurement compared to the F_a in the different drilling damage, which D_{max} was identical. So, the F_{da} can provide a more effective and actual measure for hole defects. The equation of the adjusted delamination factor can be expressed as follows

$$F_{da} = F_a + \frac{A_d}{A_{\max} - A_o}(F_a{}^2 - F_a) \tag{2}$$

where $A_{\max}$ is the delamination area related to the D_{max}, A_o is the drilled area of the D, and A_d is the delamination area in the vicinity of the drilled hole. The first part of Eq. (2) represents the size of the crack contribution, and the second part represents the damage area contribution [12]. From Eq. 2, the higher the damage on A_d is, the higher the effect on F_{da} is. However, the delamination area is minimal or maximal, F_{da} is not equal to F_a. The scheme of two critical cases in the drilling composite laminate for the drill bit is shown in Fig. 1.



(a) (b)

Fig. 1 Critical cases in drilling composite laminate
(a) minimal delamination area and (b) maximal delamination area

Therefore, a novel approach was proposed to characterize the delamination factor in this study, namely the equivalent delamination factor (F_{ed}) calculated through Eq. (3). The scheme of the F_{ed} in drilling composite laminate for the drill bit is shown in Fig. 2.

$$F_{ed} = \frac{D_e}{D} \tag{3}$$

where D_e is the equivalent delamination diameter and can be expressed as

$$D_e = \left[\frac{4(A_d + A_o)}{\pi}\right]^{0.5} \tag{4}$$

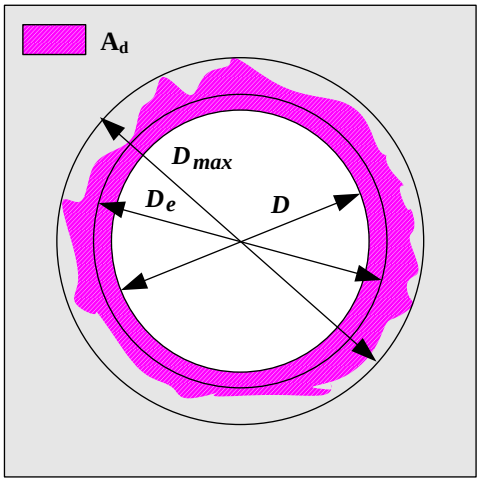


Fig. 2 Scheme of the the F_{ed} in drilling composite laminate for drill bit

This study presents a comprehensive analysis of delamination with various delamination factor models. In this analysis, the equivalent delamination factor is compared with the adjusted delamination factor and the conventional delamination factor.

Experimental Procedure

The carbon/epoxy composite material is drilled in this investigation. The laminates were fabricated from the toughened, woven carbon/epoxy of Amoco T300 fibers in 934 epoxy matrix using autoclave molding. The stacking sequence of the laminates was $[0/90]_{12S}$. Specimens of size 60 mm×60 mm were cut on a water-cooled diamond table saw. Twenty-four lamina make the plate thickness 6.0 mm. The fiber volume fraction is 0.63. The twist drills of 10 mm diameter with high speed steel were used to measure the entire induced-delamination. Drilling tests were carried out on a LEADWELL MCV-610AP vertical machining center. All tests were run without coolant at spindle speeds of 900 and 1200 rpm and feed rates of 10 and 16 mm/min, respectively. Digital images of drilling delamination area were produced from carbon fiber-reinforced composite material sections obtained by ultrasonic C-scan. The ultrasonic C-scan equipment was an AIT-5112 (Automated Inspection Technologies Inc.) unit. Commercial software (PhotoImpact 8.0) was used to extract the ultrasonic C-scan image data during scanning for measuring the delamination.

Experimental Results and Discussion

Table 1 shows the effect of the delamination parameters on various delamination factor models. Table 1 shows F_{da} and F_{ed} had better discrimination of delamination damage compared to F_a, which had the same delamination factor for test Nos. 2 to 4. Increasing A_d causes higher

delamination factor for F_{da} and F_{ed}. However, F_{da} is more clearly larger than F_{ed}. The ultrasonic C-scan shows identical F_a with various tests was shown in Fig. 3. Fig. 3 shows the delamination area in test No. 4 possesses a regular distribution in the vicinity of the drilled hole. However, the delamination area presents an irregular form, containing long and fine breaks and cracks at the hole exit for test Nos. 2 and 3. When there was a larger delamination area occurring at the hole exit, then the variance of delamination factor measured F_{da} would be more clear. Additionally, the delamination factor between F_{da} and F_{ed} for test No. 1 (delamination-free) and test No. 5 (full uniform delamination area) in Table 1 was compared. Table 1 shows the trend is almost similar to test Nos. 2 to 4. However, F_{da} is null for two critical cases (minimal or maximal delamination area). In other words, F_{da} is comparatively suitable for the regular delamination area. Table 1 shows F_{ed} is same with the F_a at two critical cases. However, the difference between F_{ed} and F_a increases with the delamination area.

Table 1 Effect of delamination parameters on various delamination factor models

Test No.	Delamination parameter				Delamination factor model		
	D (mm)	$D_{\max}$ (mm)	A_d (mm^2)	D_e (mm)	F_a	F_{da}	F_{ed}
1	10	10.000	0	10.000	1.0000	1.4375	1.0000
2	10	14.375	6.099	10.381	1.4375	1.4839	1.0381
3	10	14.375	14.977	10.911	1.4375	1.5513	1.0911
4	10	14.375	31.102	11.815	1.4375	1.6739	1.1815
5	10	14.375	83.756	14.375	1.4375	2.0664	1.4375

(a) Test No. 2 (b) Test No. 3 (c) Test No. 4

Fig. 3 Ultrasonic C-scan shows the identical F_a with various tests

Conclusion

A comparative analysis of various delamination factor models after drilling composite materials is presented in this paper. F_{da} and F_{ed} had better discrimination of delamination damage compared to F_a, which was identical at the hole exit. Additionally, the trend is almost similar to that of F_{da} and F_{ed}. F_{da} is more clearly larger than F_{ed}. However, F_{da} is null for minimal and maximal delamination area. On the other hand, the image digitalization and processing is also an essential method to obtain the delamination area after drilling a hole on composite laminates. The F_{ed} obtained through digital image processing is considered suitable for characterizing delamination at the exit of the drilled hole.

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