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The effect of chisel length and associated pilot hole on delamination when drilling composite materials

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Abstract

Drilling-induced delamination often occurs both at the entrance and the exit of the workpiece during drilling of composite material. Investigators have studied analytically and experimentally that delamination in drilling can be correlated to the thrust force of the drill. With a pre-drilled pilot hole, the delamination can be reduced significantly. Early reference reported models of drilling-induced delamination, however, the effect of chisel edge length and pilot hole diameter on delamination is rarely discussed. The optimal range of chisel edge length with respect to drill diameter is derived in this paper.

Keywords: Drilling; Composite material; Delamination; Chisel; Pilot hole; Thrust

1. Introduction

Carbon fiber-reinforced composites are well recognized for their superior mechanical properties and are widely used in aerospace, defense and transportation applications. Composite materials possess peculiar characteristics during machining. The reference of drilling of fiber-reinforced plastics reports that the quality of the machined parts is strongly dependent on drilling parameter [1,2]. Numerous studies have examined the delamination in drilling [3–7]. Most of the previous research correlates the drill geometry and feed rate to delamination, which leads to severe reduction in the load-carrying capacity of the composite part. Drilling-induced delamination occurs both at the entrance and the exit planes of the workpiece, it has been correlated with the thrust force during exit of the drill [8–10]. A rapid increase in feed rate at the end of drilling will cause the cracking around the exit edge of the hole [11]. It was also stated that the larger the feeding load, the more serious the cracking. The drill geometry is also considered the most important factor that affects drill performance [12]. Several non-traditional machining processes, i.e. laser-beam drilling [13–15], water-jet drilling (with or without abrasives) [16–18], ultrasonic drilling [19,20], electrical discharge machining (EDM) [21], have been reported as alternatives. Nevertheless, conventional drilling continues to be widely used for practical purpose. Various drilling tools are available, but the twist drill is by far the most common. The rotation and feeding of the drill bit result in relative motion between the cutting edges and the workpiece to produce chips. The efficiency of the cutting action varies, being the most efficient at the outer diameter of the drill and the least efficient at the center. In fact, the relative velocity at the drill point is zero, without cutting action. Instead, the chisel edge of the drill point pushes aside the material at the center as it penetrates into the hole. Chandrasekharan et al. developed a model to predict the thrust and torque at the different regions of cutting on a drill [22]. Their mechanistic approach exploits the geometry of the process, which is independent of the workpiece material.

Several specialized drills were developed to reduce the delamination. For example, Boeing Aircraft Co. (Seattle) developed a four-fluted spiral rotary carbide milling cutter with a unidirectional helix and a reversed-directional helix [23]. With a pilot hole, delamination can be reduced significantly. Recently, Won and Dharan investigated the effect of the chisel edge on the thrust

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force, and an innovative process model was developed to predict the advantage of a specimen with pre-drilled pilot hole [24]. A hole is pre-drilled to eliminate the thrust caused by the chisel edge, thus the threat for delamination is significantly reduced. The diameter of the pre-drilled hole is set equal to the length of chisel edge. The smaller diameter of the pilot hole cannot fully cover the chisel edge, while a larger one tends to cause undesired delamination during pre-drilling. Although valuable efforts have been made for the analysis of drilling-induced delamination, little has been reported on the effect of chisel edge length (or pilot hole diameter) on delamination. An optimal range of diameter of pilot hole associated with chisel edge length is derived in this paper.

2. Model of delamination analysis

During drilling-induced delamination, the drill movement of distance dX is associated with the work done by the thrust force F_A, which is used to deflect the plate, as well as to propagate the interlaminar crack. The energy balance equation gives

$$G_{IC}dA = F_A dX - dU \tag{1}$$

where dU is the infinitesimal strain energy, dA is the increase in the area of the delamination crack, and G_{IC} is the critical crack propagation energy per unit area in mode I. The value of G_{IC} is assumed a constant to be a mild function of strain rate by Saghizadeh and Dhahran [25].

Fig. 1 depicts the schematics of delamination with a pre-drilled central hole. The diameter of the pilot hole is selected equal to the chisel length of drill, in order to eliminate the disadvantage of the chisel-induced thrust force and avoids the threat of creating large delamination by large pre-drilled hole. In Fig. 1, the center of the circular plate is loaded by a twist drill of diameter d. F_A is the thrust force, X is the displacement, H is the workpiece thickness, h is the uncut depth under tool, $2b$ is the diameter of pilot hole, and a is the radius of existing delamination.

The isotropic bahavior and pure bending of the laminate are assumed in the model. In Eq. (1), one notes that

$$dA = 2\pi a da. \tag{2}$$

A mathematical model of a plate subjected to symmetrical bending by shearing force Q uniformly distributed along the circular inner edge of a hole is shown in Fig. 2. The deflection of the circular plate is given [26]

$$X(r) = \frac{F_A}{8\pi M} r^2\left(\log\frac{r}{a} - 1\right) - \frac{C_1 r^2}{4} - C_2 \log\frac{r}{a} + C_3 \tag{3}$$

where

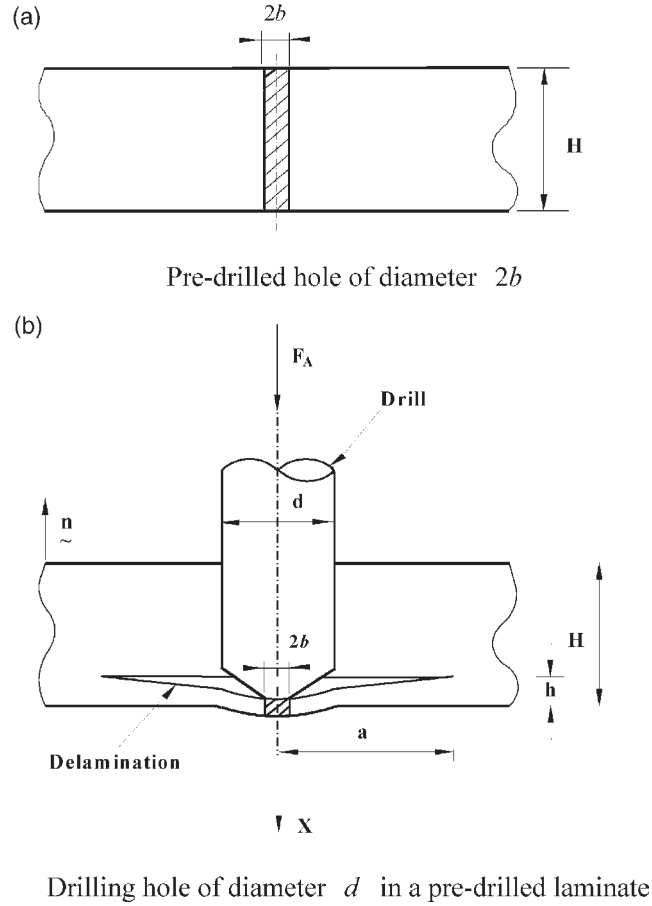

Fig. 1. Circular plate model for delamination analysis of a pre-drilled specimen.

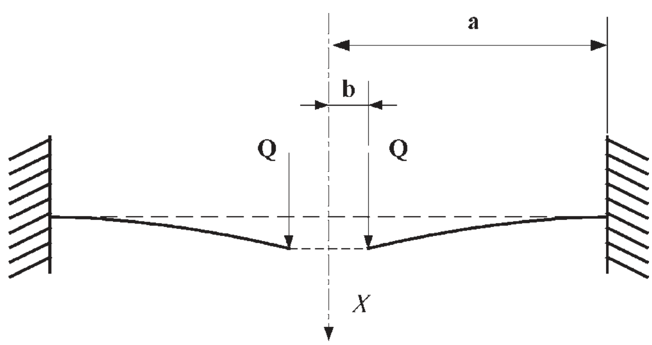

Fig. 2. A circular plate with a circular hole and distributed forces along inner edge subject to clamped boundary condition [26].

$$F_A = 2\pi b Q$$

$$C_1 = \frac{F_A}{4\pi M}\frac{(b^2 - a^2)(1-\nu) + 2b^2(1+\nu)\log(b/a)}{a^2(1-\nu) + b^2(1+\nu)}$$

$$C_2 = \frac{F_A a^2 b^2}{4\pi M}\frac{(1+\nu)\log(b/a) + 1}{a^2(1-\nu) + b^2(1+\nu)}$$

$$C_3 = \frac{F_A a^2}{16\pi M}\frac{(b^2 + a^2)(1-\nu) + 2b^2(1+\nu)\{\log(b/a) + 1\}}{a^2(1-\nu) + b^2(1+\nu)}$$

$$M = \frac{Eh^3}{12(1-\nu^2)} = \text{ flexural rigidity of the plate}$$

and ν is Poisson's ratio.

The total stored strain energy is as following

$$\begin{aligned} U &= \pi\int_b^a M\left[\left(\frac{d^2X}{dr^2} + \frac{1}{r}\frac{dX}{dr}\right)^2\right]rdr \\ &= \frac{F_A^2}{16\pi M[a^2(1-\nu) + b^2(1+\nu)]^2}(U_1 + U_2) \end{aligned} \tag{4}$$

where

$$U_1 = \frac{1}{2}(1-\nu)^2a^6-(1-\nu)[(\nu-3)-2(1-\nu)\log^2(b/a)]a^4b^2$$

$$U_2 = 4[\nu + (1+\nu^2)\log(b/a)]a^2b^4 + (1+\nu)[-2 + 2(1-\nu)\log(b/a) + 2(1+\nu)\log^2(b/a)]b^6$$

Differentiation of Eq. (4) with respect to da yields

$$\frac{dU}{da} = \frac{F_A^2(1-\nu)^2}{16\pi M} \frac{[a(1-\nu)^2 + 2(1-\nu^2)t(at+b)-4(1-\nu)^2bt\log t}{[(1-\nu)^2 + 2(1-\nu^2)t^2]^2} \tag{5}$$

where $t = b/a$ and the higher order terms of t are neglected. Similarly,

$$\frac{dX}{da} = \frac{F_A}{16\pi M} \frac{2(1-\nu)(1+\nu^2)[(1-\nu) + (1+\nu)t^2]a-2(1-\nu)bt(4+\nu^2+\nu^3)-8(1-\nu^2)bt\log t}{(1-\nu)^2 + 2(1-\nu^2)t^2}. \tag{6}$$

Substituting Eqs (2), (5) and (6) into Eq. (1) one obtains the critical thrust force at the onset of crack propagation with pre-drilled pilot hole.

$$F_A^* = \frac{4\pi}{1-\nu}\left[\frac{G_{IC}Eh^3\{(1-\nu) + 2(1+\nu)\zeta^2\}^2}{3(1+\nu)\{2(1-\nu)(1+2\nu^2)-(12-4\nu+3\nu^2+3\nu^3)\zeta^2-8(1+3\nu)\zeta^2\ln\zeta}\right]^{1/2} \tag{7}$$

where $\xi = 2b/d$. The differentiation of Eq. (7) with respect to ξ and $\partial F_A^*/\partial\xi = 0$ gives the value (ξ^*) at the minimum of the critical thrust force. Let

$$\frac{\partial F_A^*}{\partial \xi} = \xi^2(-16 + 16\nu + 26\nu^2-12\nu^3-6\nu^4-16\ln\xi-64\nu\ln\xi-48\nu^2\ln\xi) + \ln\xi + (24(8+16\nu-24\nu^2)-8\nu + 3\nu^2-19\nu^4) = 0 \tag{8}$$

When ν is 0.3, ξ^* is found 0.1176. Fig. 3 shows the critical value of diameter of pilot hole (or the chisel edge length) at various Poisson's ratio. It illustrates that the higher the Poisson's ratio (larger ν), the larger is the ξ^*.

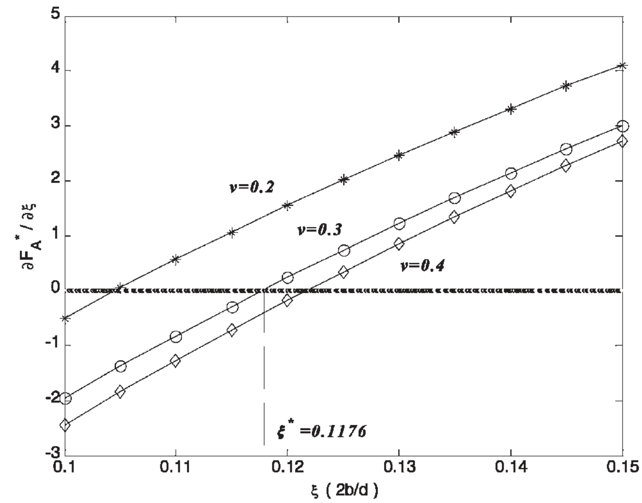

Fig. 3. Critical ratio of chisel edge length to drill diameter with various Poisson's ratio.

3. Experimental set-up

3.1. Specimen

The laminate specimens were made of toughened woven carbon/epoxy of TOHO (HTA-E30-12K) fibers in 934 epoxy matrix by autoclave molding. The stacking sequence of the laminates was $[0/90]_{12s}$. Twenty-four lamina make the plate thickness 3.6 mm. The fiber volume fraction is 0.67, the modulus of elasticity (E_1) is 189 GPa, the energy release rate (G_{IC}) is 240 J/m^2 and the Poisson ratio (ν) is 0.3 [27].

3.2. Drilling test

Drilling tests were carried out on a LEADWELL MCV-610AP vertical machining center in which the thrust force was measured with a Kistler 9273 piezoelectric dynamometer. The force signals were transmitted to Kistler 5007 charge amplifier and stored on a TEAC DR-F1 digital recorder subsequently. The drilling set-up used in data collection is shown in Fig. 4. The drill of 10 mm in diameter with high speed steel and 118° point angle was used. The chisel edge length is 1.5 or 2 mm. All drilling tests were conducted coolant free at a spindle speed of 1000 rpm and feed rates of 8, 10, 11 and 12 mm/min.

4. Results and discussions

Eq. (7) indicates that the critical thrust force for specimens with pre-drilled pilot hole is a function of material properties, the uncut thickness and the ratio of the chisel edge length to drill diameter. In the Hocheng-Dharan

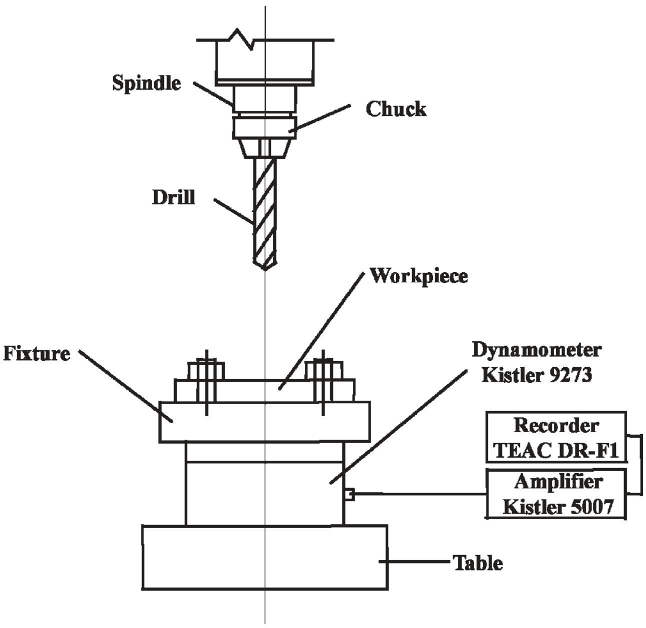

Fig. 4. Schematic of experimental set-up.

model [8] without a pilot hole, the critical thrust force is given by

$$F_A^* = \pi\left[\frac{8G_{IC}Eh^3}{3(1-\nu^2)}\right]^{1/2}. \quad (9)$$

To evaluate the effect of pilot holes on the critical thrust force value, the critical thrust force predicted by Eq. (7) was compared with that of Eq. (9) in Fig. 5 much more clearly than the early reference [24]. It shows that the critical thrust force decreases slightly for specimens with pilot holes. At $\xi^* = 0.1176$, it decreases by 11%. On the other hand, one realizes the drilling thrust force

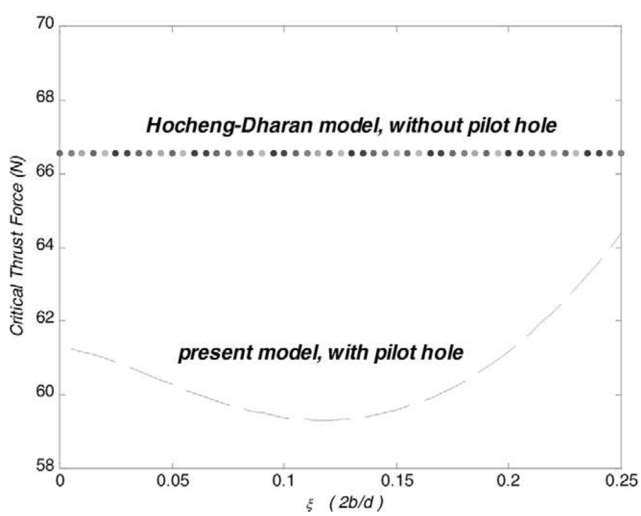

Fig. 5. Comparison of the critical thrust force predicted by present model with pilot hole and by Hocheng-Dharan model without a pilot hole (CFRP, E = 189 GPa, G_{IC} = 240 J/m^2, h = 0.15 mm and ν = 0.3).

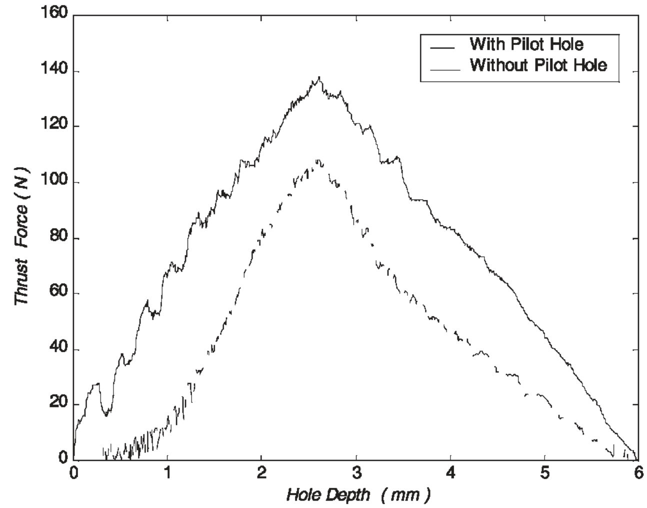

Fig. 6. Thrust force varying with hole depth (drill diameter, 10 mm; spindle speed, 1000 rpm; feed rate, 11 mm/min; ξ = 0.2; pilot hole diameter, 2 mm).

will be significantly reduced by cancellation of the chisel edge contact in drilling. Fig. 6 shows clearly that pilot hole avoids the contact of chisel edge, thus helps reduce the thrust force exerted by drill.

Fig. 7 indicated the thrust force increases with both chisel edge length and feed rate. The use of pilot hole can significantly reduce the thrust force by about 25–50%, which is more than the reduction of the critical thrust (maximum 11%). Without pilot hole, the thrust force during drilling lies quite well above the critical thrust, which implies the occurrence of delamination at commonly used feed rate. With pilot hole (e.g. ξ = 0.2), however, the thrust force during drilling can be lower than the critical value at large range of feed rates, which indicate the delamination-free drilling is achievable. The use of pre-drilled pilot hole is thus illustrated.

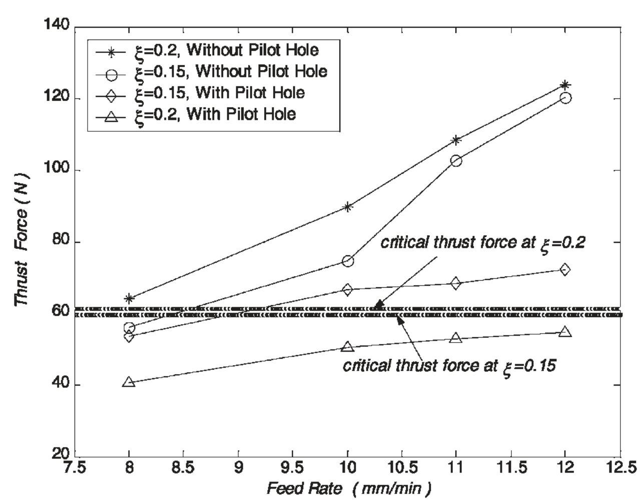

Fig. 7. Effects of pilot hole on thrust forces (drill diameter, 10 mm; ξ= 0.15 and 0.2).

Fig. 8 depicts the correlation between the experimental thrust force of various chisel length with and without pilot hole and the critical thrust force obtained by Eq. (7) and Eq. (9). A thrust force higher than the critical value will cause delamination in drilling. Jain and Yang found the effect of the chisel edge on the thrust force is linear [9]. The linear relationship is shown in Fig. 8a by the two straight lines for the cases of with and without pre-drilled pilot hole, respectively. Based on their experiment, the chisel edge is considered the major contributor to the thrust force. In the mean time, there are two models predicting the critical thrust force for delamination in the cases of with and without pre-drilling pilot hole, respectively, as shown in Fig. 8a. The intersections (points A and B) made by these experimental straight lines (regarding the effects of chisel length) and the analytical curves (regarding the predicted threshold) define the process window of chisel length (in dimensionless expression ξ). When drilling without pilot hole, the intersection A denotes the limit beyond which the increasing chisel length will produce delamination by increasing the thrust force. In case of drilling with pilot hole, point B shows the minimum of chisel length for delamination-free drilling. At suitable drilling conditions, a process window of chisel length for delamination-free drilling can be found, as illustrated in Fig. 8a.

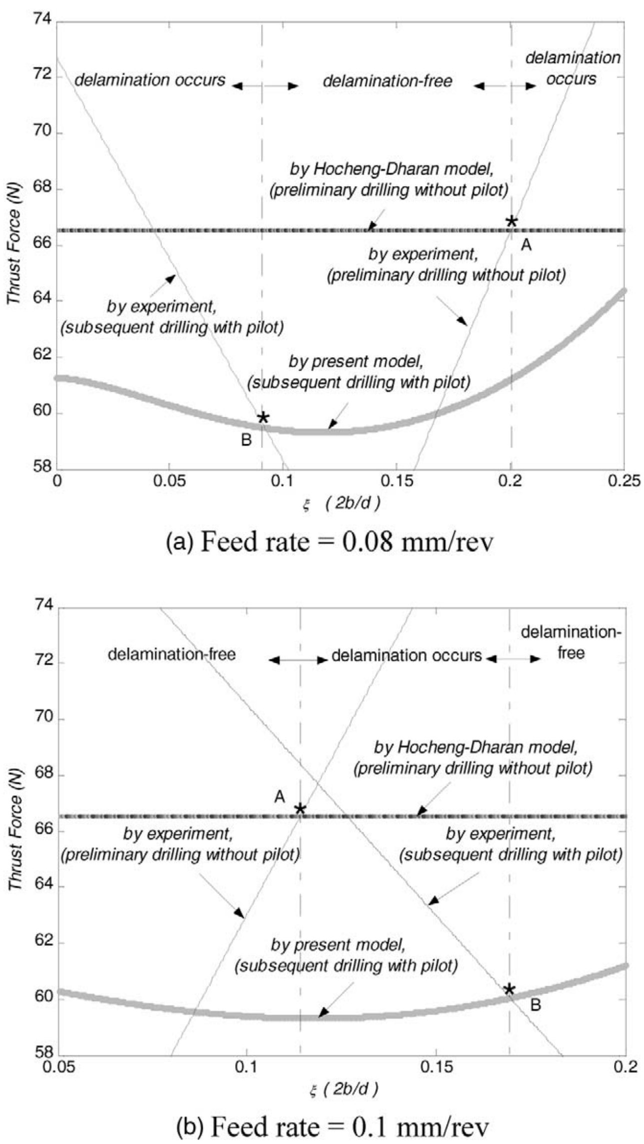

Fig. 8. Window of diameter of pilot hole associated with chisel edge (spindle speed, 1000 rpm).

The dimensionless chisel length should be designed between around 0.09 and 0.2 under the adopted drilling condition. However, when large feed rate is used, the experimental thrust force increases in agreement exclusively with existing references. In this case, the A-line moves upwards (or toward left), and B-line shifts upwards (or toward right) from Fig. 8a. The process window of chisel length can thus be closed, as shown in Fig. 8b. The experimental results of Jain and Yang in 1993 supported the proposed model that the larger the chisel edge, the larger is the thrust and the induced delamination [9]. Secondly, Won and Dharan investigated experimentally the effects of chisel edge and pilot hole on drilling composite material CFRP (with E = 189 GPa, G_{IC} = 240 J/m^2 and ν = 0.3). When the chisel ratio ξ is set at 0.18 (within the currently predicted range), the results indicated that the drilling is delamination-free with pilot hole [24]. By setting properly the drilling condition and the chisel length (or the pilot hole diameter), one can produce delamination-free hole. The current analysis explains the how to use the pilot hole to assist quality drilling of composite material.

5. Conclusions

An analytical approach to identifying the process window of chisel edge length relative to drill diameter for delamination-free drilling based on linear elastic fracture mechanics is derived in this study. The predicted critical thrust force agrees fairly with the experimental results. Experimental results indicate the critical thrust force is reduced with pre-drilled hole, while the drilling thrust is largely reduced by cancelling the chisel edge effect. A process window utilizing the pre-drilled hole can thus be opened. Controlling the ratio of chisel edge length, one can conduct medium to large hole of composite laminates drilling at higher feed rate without delamination damage. The window is influenced by the feed rate. The smaller the feed rate is, the wider the window opens.

Acknowledgements

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