Comprehensive analysis of delamination in drilling of composite materials with various drill bits

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Abstract

Beside the twist drill, the effects of various drill geometries were rarely discussed in analytical fashion. This study presents a comprehensive analysis of delamination in use of various drill types, such as saw drill, candle stick drill, core drill and step drill. In this analysis, the critical thrust force at the onset of delamination is predicted and compared with the twist drill.

Keywords: Delamination; Drilling; Saw drill; Candle stick drill; Core drill; Step drill

1. Introduction

Composite materials possess peculiar characteristics that govern behavior during machining. Drilling is the most frequently employed operation of secondary machining for fiber-reinforced materials owing to the need for structure joining. Twist drills are widely used in industry to produce holes rapidly and economically. In fact, the chisel edge of the drill point pushes aside the material at the center as it penetrates into the hole. Various drills have been used for neat drilling of composite materials, such as saw drill, candle stick drill and core drill etc.

The delamination damage caused by the tool thrust has been recognized as one of the major problems during drilling. A lot of reference of the drilling of fiber-reinforced plastics reports that the quality of the cut surfaces is strongly dependent on drilling parameter [1]. As early as 1967, the fact that a rapid increase in feed rate at the end of drilling will cause the cracking around the exit edge of the hole was found [2]. 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 [3]. Damage development and detection, new tooling design, and the influences of cutting conditions have been studied [4,5].

Haggerty and Ernst found that “spiral” point drills performed much well than the conventional ones [6]. Wu used multifaceted drills to reduce the thrust force [7]. Doerr et al. designed the drill to cut materials toward the hole center and to shear at the hole edge [8]. The influence of tool wear and the resulting increase of thrust were discussed [9–12]. Koening et al. investigated the effect of processing variables on drilling damage [13]. A general overview of the various possibilities for composites machining can be found [14].

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. The first analytical model to determine the critical thrust force of the drill was formulated by Hocheng and Dharan [15]. They employed linear elastic fracture mechanics (LEFM) method and solved for the critical thrust force during exit of the drill. The influence of tool wear and the resulting increase of thrust were discussed [9–12]. Koening et al. investigated the effect of processing variables on drilling damage [13]. A general overview of the various possibilities for composites machining can be found [14].

These works simplified the drilling thrust force by a representative single concentrated central load. Beside the twist drill, the effects of various drill geometries were rarely discussed in analytical fashion. This study presents a comprehensive analysis of delamination in use of various drill types, such as saw drill, candle stick drill, core drill and step drill. In this analysis, the critical thrust force at the onset of delamination for various special drills is mathematically predicted and compared with the conventional twist drill.
2. Delamination analysis

Delamination is considered as the principal failure model in drilling of composite materials. It is analyzed using classical plate bending theory and linear elastic fracture mechanics. The possible mechanisms causing delamination at both exit and entry are described, and the critical thrust and cutting force leading to the onset of delamination are predicted. In consideration of the expense of time and cost, an analytical approach is endeavored to embody the aspects of materials and process parameters in a model to predict the onset of delamination [19].

2.1. Physical model

Fig. 1 depicts the drilling of composite materials. At the propagation of 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

\[
G_{IC} dA = F_A dX - dU
\]

where \( dU \) is the infinitesimal strain energy, \( dA \) the increase in the area of the delamination crack, and \( G_{IC} \) the critical crack propagation energy per unit area in mode I.

2.2. Mathematical analysis

2.2.1. Conventional concentrated central load (twist drill) [15]

Fig. 2 depicts the schematics of delamination. In Fig. 2, the center of the circular plate is loaded by a twist drill of diameter \( d \). \( F_A \) is the thrust force, \( X \) the displacement, \( H \) the workpiece thickness, \( h \) the uncut depth under tool, and \( a \) the radius of delamination. The isotropic behavior and pure bending of the laminate are assumed in the model.

For a circular plate subject to clamped ends and a concentrated load, the stored strain energy \( U \) is

\[
U = \frac{8\pi M X^2}{d^2}
\]

where

\[
M = \frac{Eh^3}{12(1-\nu^2)}
\]

and the displacement \( X \) is

\[
X = \frac{F_A a^2}{16\pi M}
\]

The thrust force at the onset of crack propagation can be calculated

\[
F_A = \pi \sqrt{\frac{32G_{IC} M}{\pi}} = \pi \left( \frac{8G_{IC} Eh^3}{3(1-\nu^2)} \right)^{1/2}
\]

The applied thrust force should not exceed this value, which is a function of the material properties and the uncut thickness, to avoid delamination. Thrust force can be correlated with feed rate.

2.2.2. Circular load (saw drill)

Fig. 3 depicts a saw drill and the induced delamination, where \( c \) is the radius of saw drill. Saw drill can acquire better machining quality in drilling composite laminates. One reason is that saw drill utilizes the peripherally distributed thrust for drilling the composite laminates.

The critical thrust force \( (F_S) \) at the onset of crack propagation can be calculated

\[
F_S = \pi \sqrt{\frac{2G_{IC} M}{1 - 2\nu^2 + \nu^2}}
\]
where $s = c/a$. The comparison of $F_S$ and $F_A$ in Eqs. (6) and (5) gives

$$F_S = \frac{1}{\sqrt{1-2s^2 + s^4}}$$  \hspace{1cm} (7)

2.2.3. Concentrated centered load associated with circular load (candle stick drill)

Fig. 4 depicts the schematics of a candle stick drill and the induced delamination. Candle stick drill is extensively used for drilling composite materials. The thrust force of the candle stick drill can be considered as a concentrated center load plus the distributed circular load. Using the method of superposition, the thrust force $F_C$ can be expressed as follows:

$$F_C = p_1 + p_2$$  \hspace{1cm} (8)

where $p_1$ and $p_2$ are the central concentrated force and the peripheral circular force, respectively, as shown in Fig. 4.

The energy balance equation can be expressed as follows:

$$G = \frac{2\pi a}{16aM} + \frac{p_1^2}{16aM} \left( a - \frac{c^2}{a} + \frac{e^2}{a^2} \right)$$  \hspace{1cm} (9)

where the subscripts 1 and 2 denote the variables for the central concentrated force and the peripheral circular force, respectively. Let

$$p_2 = \alpha p_1$$  \hspace{1cm} (10)

The thrust force $p_1$ can be calculated

$$p_1 =\pi \sqrt{\frac{32GIC}{1 + \alpha^2(1 - 2s^2 + s^4)}}$$  \hspace{1cm} (11)

Substituting Eqs. (10) and (11) into Eq. (8), one obtains the thrust force of the candle stick drill at the onset of crack propagation:

$$F_C = \pi(1 + \alpha) \sqrt{\frac{32GIC}{1 + \alpha^2(1 - 2s^2 + s^4)}}$$  \hspace{1cm} (12)

The comparison of $F_C$ and $F_A$ in Eqs. (12) and (5) gives

$$\frac{F_C}{F_A} = \frac{1 + \alpha}{\sqrt{1 + \alpha^2(1 - 2s^2 + s^4)}}$$  \hspace{1cm} (13)

2.2.4. Distributed circular load (core drill)

Fig. 5 depicts the schematics of a core drill and the induced delamination. Since the tool-work contact is located in a circular area at bottom of drilling core, the thrust force of the core drill is considered a downward area load ($P_1$) subtracted by an upward area load ($P_2$), as shown in Fig. 5. Let

$$P_2 = (1 - \beta^2)P_1$$  \hspace{1cm} (14)

where $r$ is the thickness of core drill, and $\beta$ the ratio between thickness and radius of core drill (namely, $t = \beta r$).

The energy balance equation can be expressed as follows:

$$G = \frac{2\pi a}{16aM} + \frac{P_1^2}{16aM} \left( a - \frac{c^2}{a} + \frac{e^2}{a^2} \right) - \frac{P_2^2}{16aM} \left( a - \frac{c^2}{2a} \right)$$  \hspace{1cm} (15)

where the subscripts 1 and 2 denote the variables for the downward force and the upward force, respectively.

For a laminate subject to an uniformly distributed load (Fig. 6), the following analysis is available [20]. The outer and inner deflection of a circular plate of radius $a$, which is clamped and subjected to a uniformly distributed load over a central circular area of radius $r$, is given by

(i) $0 \leq r \leq c$ (inner portion):

$$X = \frac{P_1}{64aM} \left[ (4r^2 - 3c^2 + 4c^2 \ln \frac{c}{r}) - 2r^2 \left( \frac{c^2}{a^2} - 4 \ln \frac{c}{a} + \frac{c^2}{a^2} \right) \right]$$  \hspace{1cm} (16)
The stored strain energy is

\[ U_1 = \pi \int_0^c M \left( \frac{d^2 X}{dr^2} + \frac{1}{r} \frac{dX}{dr} \right)^2 r dr \]

\[ = \frac{P_1^2}{64 \pi M} \left( \frac{2\alpha^2 + c^2 - r^2}{a^2} \frac{e}{2a^2} \right) \frac{2\alpha^2}{a^2} + 8\alpha^2 \left( \frac{c}{a} \right)^2 \]  

(18)

(ii) \( c \leq r \leq a \) (outer portion):

\[ U_2 = \pi \int_c^a M \left( \frac{d^2 X}{dr^2} + \frac{1}{r} \frac{dX}{dr} \right)^2 r dr \]

\[ = \frac{P_1^2}{64 \pi M} \left( \frac{2\alpha^2 - 2c^2 + \frac{c^4}{2c^2}}{2c^2} - \frac{8\alpha^2}{a^2} \right) \]

\[ = \frac{P_1^2}{64 \pi M} \left( \frac{2\alpha^2 - 2c^2 + \frac{c^4}{2c^2}}{2c^2} - \frac{8\alpha^2}{a^2} \right) \]  

(19)

The critical thrust force \( P_1 \) at the onset of crack propagation can be calculated:

\[ P_1 = \frac{\sqrt{32G_{IC}M}}{1 - (1 - \beta)^{1/2}} \]  

(20)

where \( s = c/a \). The comparison of \( P_1 \) and \( F_A \) in Eqs. (20) and (5) gives

\[ \frac{P_1}{F_A} = \frac{1}{\sqrt{1 - (1/2)^2}} \]  

(21)

2.2.5. Stepwise distributed circular load (step drill)

DiPaolo et al. uses an experimental setup that exploits the technology of video to view the complete crack growth as the drill emerges from the bottom side of the workpiece [21]. It reported that the crack growth is divided into three regions. Region 1 is identified as the initial growth of the crack, mostly within the drill radius, formed under the forces due to the chisel edge and cutting lips of the drill. The second region, the end of which is marked with the end of thrust force, is characterized by crack growth due to the force exerted by the cutting lips only. The third region of crack growth is due to the drill force after the cutting lips and the chisel edge exited the laminate. In order to realize the procedure of drilling composite plate with a step drill (Fig. 7(a)), the whole drilling processes were divided into eight steps as shown Fig. 7(b)-(e). The sequence shows how the step drill
emerges from the laminate. Before the chisel edge emerges from the laminate, the chisel edge and primary cutting lips exert an uniformly distributed load on the laminate. When the chisel edge exits the laminate, the force evolves to a distributed circular force. The critical thrust force \( F_1 \) at the onset of crack propagation can be calculated:

\[
(F_1)_i = \pi \left[ 1 - \left( \frac{i\xi}{n} \right)^2 \right] \times \frac{32GKcM}{\left[ (1 - (i\xi)^2) - (1/2)n^2 [1 - (i\xi)^2] \right]^{i - 1}} 
\]

where \( n \) is the number of sequential increment of secondary cutting lips in action, \( \xi \) the divided thickness of the last laminar according to \( n \). The critical thrust force \( (F_1)_i \) based on the concentrated force assumption is given in Eq. (5).

Thus, the ratio between the two critical thrust forces becomes

\[
\frac{(F_2)_i}{(F_1)_i} = \frac{\left[ 1 - (i\xi)^2 \right]}{\sqrt{\left[ 1 - (i\xi)^2 \right] - (1/2)n^2 [1 - (i\xi)^2]}} 
\]

where \( i = 1 - n \) indicates the chisel edge and the primary cutting lips that emerged from the laminate, the secondary cutting lips cut and bend the last laminar.

3. Discussions and summary

The reduction of critical thrust force for various drills is shown in Table 1. The physical effects of various drill geometry can be illustrated mathematically as follows:

1. For saw drill, the case of \( s = 0 \) reduces the twist drill, while \( a \) approaches to 1 allows for very high critical thrust force.

2. For candle stick drill, the case of \( \alpha = 0 \) reduces to the twist drill case. While \( \alpha = \infty \) approaches to the core drill.

3. For core drill, the case of \( s = 0 \) and \( \beta = 1 \) reduces to the twist drill.

4. For step drill, the case of \( i = \xi = 0 \) and \( x = 0 \) reduces to the twist drill case. While \( i = \xi = 0 \) and \( \beta = 1 \) approaches to the core drill.

Table 1

<table>
<thead>
<tr>
<th>Twist drill</th>
<th>Saw drill</th>
<th>Core drill</th>
</tr>
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<tbody>
<tr>
<td>( s = 0 )</td>
<td>( a = 0 )</td>
<td>( n = 0 )</td>
</tr>
<tr>
<td>( \alpha = 0 )</td>
<td>( \alpha = \infty )</td>
<td>( \alpha = \infty )</td>
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References


