A Treatment of Drilling-Induced Delamination of Composite Materials

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ABSTRACT
Delamination is among the most serious concerns during drilling of fiber-reinforced composite materials, while drilling is the most frequently employed operation of secondary machining owing to the need for structure joining. However, delamination of various sizes often occurs, which threatens the long-term reliability of the composite structure. This chapter presents a comprehensive analysis of delamination in use of various drills. The critical thrust forces at the onset of delamination are theoretically predicted and compared with the case using twist drill. The well-known advantage of industrial uses such special drills as candle stick drill, saw drill, core drill and step drill is fundamentally illustrated. In addition, the effects of pilot hole, drill eccentricity and tool wear, and back-up at exit for various drills on delamination are analyzed in this chapter. A guide for drill design can be developed based on the proposed models, and this approach can be extended to examine the effects of various drill or future innovative drill design.

The evaluation of the drilling-induced delamination damage in the material is rather difficult, particularly for the carbon fiber-based composites, which are optically disadvantageous for the conventional visual inspection. Computerized tomography (CT) widely used in medical industry is proposed for this purpose. It is compared to the other ultrasonic technique and is demonstrated a feasible and an effective tool for the evaluation of drilling-induced delamination. Drilling experiment using various drills is conducted, and the produced delamination is measured by the proposed technique. The results show CT can successfully help illustrate the correlation between the thrust force and the drilling-induced delamination.

1. INTRODUCTION
1.1 Background and Problem Statement
Fiber reinforced plastics (FRPs), such as carbon fiber reinforced plastics (CFRPs) and glass fiber reinforced plastics (GFRPs), have been used widely in aerospace, defense and transportation structures as well as sports and leisure goods owing to their high specific stiffness, high specific strength, high damping, high corrosion resistance and low coefficient of thermal expansion. With drastic increase in oil price, problems of saving energy in, such as transportation, is deeply concerned lately. Boeing has announced that as much as 50\%\% of the primary structure, including the fuselage and wing, on the Dreamliner-787 will be made of composite materials. Dreamliner-787 will bring the economic advantage of large jet transports to save 20\% more fuel than any other airplanes of their size [1]. In addition, composite materials possess the advantage over rival aluminum alloys as they provided greater durability, reduced maintenance, and increased potential for future development. It is also possible that sensors will be embedded into the composite structures to acquire and to monitor the health and help schedule maintenance.

Due to the anistropic and inhomogeneous property of FRPs, drilling FRPs causes some problems, such as delamination, burrs, swelling, splintering and fiber pullout, which do not occur in other materials. On the other hand, bolt-joining FRPs structures to other materials are often
required, and the joining efficiency is largely dependent on the quality of machined holes. Several non-traditional machining processes, such as laser-beam drilling, water-jet drilling (with or without abrasive additives), ultrasonic drilling, electrical discharge machining (EDM), etc. have been reported as alternatives on FRPs for machining holes. Traditional drilling with twist drill still remains by far the most common in industry to produce holes rapidly and economically. However, the geometry and the velocity of cutting edge for twist drill are not constant, but vary along the cutting edge. In general, the rotation and feed of the drill bit result in relative motion between the cutting edges and the workpiece to form the chips. The cutting speed along each cutting edge varies as a function of the distance from the axis of rotation. 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. Various drills, moreover, have been used for practical drilling of composite materials, such as saw drill, candle stick drill, core drill and step drill etc.

1.2 Literature Review

The most important phases during drilling composite laminates are close to the entry and exit where extensive damage in terms of delamination can occur due to 'peel-up' and 'push-out' effects respectively. The delamination damage caused by the tool thrust has been known as one of the major concerns during drilling and it is believed that there is a “critical thrust force” below which no damage occurs [2]. A lot of references of the drilling of fiber-reinforced plastics report that the quality of the cut surfaces is strongly dependent on geometry and material of drill and drilling parameter [3-23]. 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 [24]. It was also stated that the larger the feeding load, the more serious the cracking. Damage development and detection, new tooling design, and the influences of cutting conditions have been studied [25-26]. Friedrich et al. cited the “split” or “crankshaft” point as being very popular in the aircraft and automotive industries [27]. Haggerty and Ernst found that “spiral” point drills performed much well than the conventional ones [28]. Wu used multifaceted drills to reduce the thrust force [29]. Doerr et al. designed the drill to cut materials toward the hole center and to shear at the hole edge [30]. 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 [5, 31-33]. A general overview of the various possibilities for delamination-free drilling of composite materials can be found in [34].

Generally, thrust forces by drill bits generate interlaminar stresses between plies. When the local compressive stresses at the hole periphery exceed the interlaminar strength in the matrix rich region, crack is initiated and propagates in a stable manner. In association with the concerns of the structural integrity of the laminate, the edge delamination during drilling leads to a severe reduction in load-carrying capacity of the composite part. 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 [35]. They employed linear elastic fracture mechanics (LEFM) method and solved for the critical thrust force that relates the delamination of composite laminates to drilling parameters and composite material properties. Jain and Yang extended this theory by taking into consideration of the anisotropy of the composite material [8-9]. They developed a model for correlating the feed rate with the onset of delamination [8].
Based on a continuum mechanics approach, Everstine and Rogers formulated a model for the prediction of minimum cutting force for parallel fibers at 0° orientation [36]. Sadat et al. used the finite element analysis to predict the load causing delamination in graphite/epoxy material in a drilling operation [37]. Zhang et al. presented a general closed-form mechanical model for predicting the critical thrust force at which delamination is initiated at different ply location [38]. These works, however, simplified the drilling thrust force as a single concentrated central load. Beside the twist drill, the effects of various drill geometries were rarely discussed in analytical fashion. Therefore, the theoretical analysis of critical thrust force for various drill geometries can give wealth information about drilling-induced delamination of composite materials.

2. FUNDAMENTAL THRUST FORCE-BASED DELAMINATION MODEL

In drilling of composite laminates, the uncut thickness to withstand the drilling thrust force decreases as the drill approaches the exit plane. The laminate at the bottom can be separated from their interlaminar bond around the hole edge. At some point the loading exceeds the interlaminar bonding strength and delamination occurs. One approach is to perform the experimental work and hold the machinability data to account for delamination of different materials for various tools and machining parameters [6]. 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 [39].

Fig. 2.1 depicts the model of drilling in 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, $dA$ 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 [40], the applicability of fracture mechanics to conventional isotropic materials has been demonstrated in the early reference [41].
Fig. 2.2 depicts the schematics of delamination model. In Fig. 2.2, 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, and $a$ is the radius of delamination.

The isotropic behavior and pure bending of the laminate are assumed in the model. In Eq. (2.1), one notes that

$$dA = \pi(a + da)(a + da) - \pi a^2 = 2\pi da$$

For a circular plate subject to clamped ends and a concentrated load, the stored strain energy $U$ as shown in [42]

$$U = \frac{8\pi MX^2}{a^2}$$

where $M$ is the stiffness per unit width of the fiber reinforced material given by

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

$E$ is Young’s Modulus and $\nu$ is Poisson’s ratio for the material, and the displacement $X$ as shown in [42]

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

The thrust force at the onset of crack propagation can be calculated [35]

$$F_A = \pi \sqrt{32 G_K M}$$

$$= \pi \left[ \frac{8 G_K Eh}{3(1 - \nu^2)} \right]^{\frac{3}{2}}$$

To avoid the drilling-induced delamination, the applied thrust force should not exceed this value, which is a function of the material properties and the uncut thickness. The thrust force can be correlated with feed rate. When the uncut thickness progressively decreases, the strategy will be to drill as fast as practically permissible in the beginning, and the feed rate should be gradually reduced as the tool approaches to the exit. Correlation with thrust force and dimensionless hole depth is shown in Fig. 2.3 [35].
3. EFFECTS OF VARIOUS GEOMETRY OF DRILL BITS

3.1 Basic Forms

3.1.1 Saw drill [18]

Fig. 3.1 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 the saw drill utilizes the peripheral distribution of thrust for drilling the composite laminates.

![Circular plate model for delamination analysis (saw drill)](image)

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

\[
F_S = \pi \sqrt{\frac{32G_KM}{(1-2s^2+s^4)}}
\]

where \( s = c/a \). The comparison of \( F_S \) and \( F_A \) in Eq. (3.1) and Eq. (2.6) gives

\[
\frac{F_S}{F_A} = \sqrt{1-2s^2+s^4}
\]

Fig. 3.2 depicts the ratio between the critical thrust force of saw drill and twist drill varied with drill diameter and the crack size. It is seen that the value of thrust force ratio remains little
affected up to $s \approx 0.5$ (i.e. the drill is small compared with the delamination), and increases fast with increasing $s$. The ratio is very high when the delamination size ($a$) is close to the drill radius ($c$), namely $s$ approaches to 1.

As pointed out by DiPaolo et al., the delamination of size less than drill is not of concern because it is drilled out afterwards anyway [43]. When the delamination grows beyond the drill radius, the saw drill (applying the circular force) can sustain much larger thrust force than the twist drill (applying the concentrated force), as shown in Fig. 3.2. Hence, the saw drill can offer higher feed rate to drill the composite materials without causing delamination.

![Fig. 3.2 Critical thrust ratio between saw drill and twist drill](image)

### 3.1.2 Candle stick drill [18]

Fig. 3.3 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 ($p_1$) plus the distributed circular load ($p_2$).

![Fig. 3.3 Circular plate model for delamination analysis (candle stick drill)](image)

The thrust force of the candle stick drill ($F_c$) at the onset of crack propagation can be calculated.
\[ F_c = \pi (1 + \alpha_c) \sqrt{\frac{32GcM}{1 + \alpha_c^2 (1 - 2s^2 + s^4)}} \]  
(3.3)

where \( \alpha_c \) is the ratio of the distributed circular load and the concentrated center load.

The comparison of \( F_c \) and \( F_A \) in Eq.(3.3) and Eq.(2.6) gives

\[ \frac{F_c}{F_A} = \sqrt{\frac{1 + \alpha_c^2 (1 - 2s^2 + s^4)}} \]  
(3.4)

Results of the critical thrust force predicted by the candle stick drill are presented in Fig. 3.4. The candle stick drill exerts a thrust force on the laminate, which is composed of the concentrated central force and the peripheral circular force. Since the total thrust force is distributed toward the periphery at a ratio of \( \alpha_c \), the drill is expected to be advantageous for allowing larger critical thrust force at the onset of delamination, similar to the effect of saw drill. Fig. 3.4 illustrates that the more the thrust force is distributed toward the periphery (larger \( \alpha_c \)), the larger becomes the critical threshold. In fact, the candle stick drill is physically the intermediate between the twist drill and the saw drill, and mathematically the general solution is reducible to the particular cases of both twist drill (completely concentrated force) and the saw drill (completely distributed circular force). One notices in Fig. 3.4, that \( \alpha_c = 0 \) represents the twist drill case, while the increasing \( \alpha_c \) approaches to the saw drill case.

![Critical thrust ratio between candle stick drill and twist drill](image)

**Fig. 3.4** Critical thrust ratio between candle stick drill and twist drill

### 3.1.3 Core drill [18]

Fig. 3.5 depicts the schematics of a core drill and the induced delamination. The outer and inner deflection of a circular plate of radius \( a \), which is clamped and subjected to annular distributed load over a round area of radius \( c \), is given [42]. \( c^- \) and \( c \) are the inner and outer radius of core drill, respectively. \( t \) is the thickness of core drill, and \( \beta \) is the ratio between thickness and radius of core drill (namely, \( \beta = t / c \)).
One obtains the thrust force of the core drill \( F_R \) at the onset of crack propagation as

\[
F_R = \pi \left\{ \frac{32G_icM}{1 - K_1s^2 + K_2s^4} \right\}^{1/2}
\]

where

\[
K_1 = (2 - 2\beta + \frac{3\beta^2}{2}) + \frac{4(1 - \beta)^2}{\beta(2 - \beta)} \ln(1 - \beta)
\]

\[
K_2 = \frac{(2 - 4\beta + 5\beta^2 - 3\beta^3 + \beta^4)}{2} + \frac{2(1 - \beta)^2(2 - 2\beta + \beta^2)}{\beta(2 - \beta)} \ln(1 - \beta)
\]

The comparison of \( F_R \) in Eq.(3.5) and \( F_A \) in Eq.(2.6) gives

\[
\frac{F_R}{F_A} = \left\{ \frac{1}{1 - K_1s^2 + K_2s^4} \right\}^{1/2}
\]

The results of the predicted critical thrust force for the core drill is presented in Fig. 3.6. Since the total thrust force is uniformly distributed in an annular area (at the ratio of \( \beta = \frac{t}{c} \)) rather than concentrated at center, the drill is expected to be advantageous for allowing larger critical thrust force responsible for later onset of delamination. Fig. 3.6 illustrates the more the thrust force is distributed toward the periphery (larger \( s \)), the higher becomes the critical threshold. One notices in Fig. 3.6, that \( \beta = 0 \) approaches to the saw drill case of circular load. In Fig. 3.5, it is shown that \( \beta \) is determined by the thickness of core drill.
3.1.4 Step Drill [20]

The step drill can be considered as composed of primary stage (of diameter $2b_T$) and secondary stage (of diameter $2c$) as shown in Fig. 3.7. DiPaolo et al. uses an experimental setup to view the crack growth as the drill emerges from the bottom side of the workpiece [43]. The eventual crack growth is due to the drill force of cutting lips after the chisel edge exited the laminate, similar to the case of step drill considered here. Fig. 3.7 depicts the schematics of a step drill and the induced delamination, where $F_T$ is the thrust force and $Q$ is the circular load exerted by the secondary cutting lips. The isotropic behavior and pure bending of the laminate are assumed in the model. A mathematical model of a plate subjected to symmetrical bending by the force $Q$ along the circular edge of a hole is shown in Fig. 3.7.

![Fig. 3.6 Critical thrust ratio between core drill and twist drill](image)

![Fig. 3.7 Circular plate model for delamination analysis (step drill)](image)
The critical thrust force at the onset of crack propagation with a step drill when the final (secondary) stage of drilling proceeds.

\[ F_T = \frac{\sqrt{2\pi} \left[ 32G_{IC}M \left( 1 - \nu + 2(1 + \nu)\kappa^2 \right)^2 \right]}{1 - \nu \left( 1 + \nu \right) \left( 2(1 - \nu)(1 + 2\nu^2) - (12 - 4\nu + 3\nu^2 + 3\nu^3)\kappa^2 - 8(1 + 3\nu)\kappa^2 \ln \kappa \right)} \]  

\[ F_A = \frac{\sqrt{2}}{1 - \nu} \left[ \frac{(1 - \nu) + 2(1 + \nu)\kappa^2}{1 + \nu \left( 2(1 - \nu)(1 + 2\nu^2) - (12 - 4\nu + 3\nu^2 + 3\nu^3)\kappa^2 - 8(1 + 3\nu)\kappa^2 \ln \kappa \right)} \right] \]  

where \( \kappa = b_T / c \). The ratio between \( F_T \) and \( F_A \) is

\[ \frac{F_T}{F_A} = \frac{1}{1 - \nu} \left[ \frac{(1 - \nu) + 2(1 + \nu)\kappa^2}{1 + \nu \left( 2(1 - \nu)(1 + 2\nu^2) - (12 - 4\nu + 3\nu^2 + 3\nu^3)\kappa^2 - 8(1 + 3\nu)\kappa^2 \ln \kappa \right)} \right]^{-\frac{1}{2}} \]  

Fig. 3.8 depicts the ratio between the critical thrust force of step drill and twist drill varying with the drill diameter ratio. It is seen that the value of thrust force ratio increases with increasing \( \kappa \), which means the circular thrust force is more distributed outwards. It also shows that the increasing Poisson’s ratio (large \( \nu \)) has a mild effect on the reduction of the critical thrust force.

3.2 Composite Drills

3.2.1 Core-center drill [44]

The chisel edge produces normal stress which can be large enough to open the ply interface (crack opening mode I), before the chisel edge of twist drill can get through the laminate material. DiPaolo et al. found spalling occurred via two types of damage mechanism [43]. The first and the most dominant one was the opening mode of fracture, Mode I, produced by the downward thrust force from the chisel edge onto the last lamina. The second type of damage was tearing and twisting. The spallings were subjected to a tearing fracture mode, Mode III, as a result of the drilling torque and a twisting due to the combination of the downward thrust force and the back rake angle along the cutting lips. Langella et al. presented a mechanistic model for predicting the thrust and torque during composite materials drilling [45]. They specified the action of the chisel edge for twist drill on thrust increases with the feed rate and may account for over 80% of the total force needed to drill a hole. The torque-associated crack propagation in Mode III is therefore considered of secondary significance in the analysis of drilling-induced delamination.
Fig. 3.9 depicts the schematics of a core-center drill and the induced delamination. The center of the circular plate is loaded by a twist drill of radius \( c \). \( F_{cc} \) is the thrust force of core-center drill. The thrust load of core-center drill is simulated by the composition of twist drill and core drill, namely the summation of the concentrated center load \( (l_2) \) and the annular area load \( (l_1) \).

The thrust force of the core-center drill \( (F_{cc}) \) at the onset of crack propagation can be obtained.

\[
F_{cc} = \pi (1 + \gamma) \left\{ \frac{32G_{lc}M}{1 + \gamma^2 (1 - K_is^2 + K_is^4)} \right\}^{1/2}
\] (3.9)

where \( \gamma \) is the ratio of the central concentrated force and the annular area force.

The comparison of \( F_{cc} \) and \( F_A \) gives

\[
\frac{F_{cc}}{F_A} = \frac{(1 + \gamma)}{\sqrt{1 + \gamma^2 (1 - K_is^2 + K_is^4)}}
\] (3.10)

Results for the critical thrust force predicted by the core-center drills are presented in Fig. 3.10. The core-center drill exerts a thrust force on the laminate, which is composed of the concentrated central force and the annular area force. Since the total thrust force is distributed toward the periphery at a ratio of \( \gamma \), the drill is expected to be advantageous in allowing a larger critical thrust force at the onset of delamination, similar to the effect of core drill. Fig. 3.10 illustrates that the more the thrust force is distributed toward the periphery (smaller \( \beta \)), the larger becomes the critical threshold. The comparison of Fig. 3.6 and Fig. 3.10 in \( \beta \) shows the core-center drill performs much better than core drill apparently. The more \( \gamma \), the more critical thrust force. In fact, the core-center drill is physically an intermediate between the twist drill and the core drill, and mathematically the general solution is reducible to the particular cases of both twist drill (completely concentrated force) and the core drill (completely circular area force). One
notices in Fig. 3.10, that $\gamma = 0$ represents the twist drill case. While the value of $\gamma$ over 1, the critical thrust force varies in a narrow range.

![Graphs showing critical thrust ratio between core-center drill and twist drill](image)

(a) $\beta = 0.1$  
(b) $\beta = 0.3$  
(c) $\beta = 0.5$

**Fig. 3.10** Critical thrust ratio between core-center drill and twist drill

### 3.2.2 Core-saw drill [46]

Fig. 3.11 depicts the schematics of a core-saw drill and the induced delamination. In Fig. 3.11, $c^*$ is the inner radius of core drill, $b_s$ is the radius of saw drill, $r^*$ is the distance between $c^*$ and $b_s$, and $\phi$ is the ratio between $r^*$ and radius of core drill (namely, $r^* = \phi^* r^*$). The thrust force of the core-saw drill can be considered as a periphery circular load plus the annular area load.
The thrust force of the core-saw drill ($F_{CS}$) at the onset of crack propagation can be calculated.

$$F_{CS} = \pi (1 + \lambda) \left( \frac{32G_{IC}M}{\lambda^2 + \left[ 1 - \left[ K_1 + \lambda^2(1 - \beta - \phi)^2 \right] s^2 + [K_2 + \lambda^2(1 - \beta - \phi)^4] s^4 \right]} \right)^{1/2}$$  \hspace{1cm} (3.11)

where $\lambda$ is the ratio of the periphery circular force and the annular area force.

The comparison of $F_{CS}$ and $F_A$ gives

$$\frac{F_{CS}}{F_A} = \frac{(1 + \lambda)}{\sqrt{\lambda^2 + \left[ 1 - \left[ K_1 + \lambda^2(1 - \beta - \phi)^2 \right] s^2 + [K_2 + \lambda^2(1 - \beta - \phi)^4] s^4 \right]}}$$  \hspace{1cm} (3.12)

Results for the critical thrust force predicted by the core-saw drill is presented in Fig. 3.12. The core-saw drill exerts a thrust force on the laminate, which is composed of the periphery circular force and the circular area force. Since the total thrust force is distributed toward the periphery at a ratio of $\eta$ and $\phi$, the drill is expected to be advantageous in allowing a larger critical thrust force at the onset of delamination, similar to the effect of core drill. Fig. 3.12 illustrates that the more the thrust force is distributed toward the periphery (smaller $\beta$ and $\phi$, larger $\eta$), the larger becomes the critical threshold. Compare with Fig. 3.6 and Fig. 3.12 in $\eta$ and $\beta$, the core-saw drill much better than core drill apparently.
Fig. 3.12  Critical thrust ratio between core-saw drill and twist drill

3.3 Comparison and Reducible Relationship among Drill Bits [34]

The reducible relationships of critical thrust force among the special drills are shown in Table 3.1, which are associated with the mathematical expressions as follows.

(1) The saw drill ( ) of \( \frac{s}{a} = 0 \) reduces to the twist drill case. With the
increasing $s$ approaches to 1, the threshold of the thrust force becomes very high showing the advantageous effects of the saw drill.

(2) For candle stick drill ( ), $\alpha$ (which is the ratio of circular load to centered load) = 0 reduces to the case of twist drill with concentrated central load only, while $\alpha = \infty$ approaches to the use of saw drill with circular load exclusively.

(3) The core drill ( ) of $\beta$ (which is $\frac{L}{C}$) = 0 reduces to the use of saw drill, while $\beta = 0$ approaches to the use of saw drill.

<table>
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<tr>
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<th>twist drill</th>
<th>saw drill</th>
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<tr>
<td>(1) Saw drill</td>
<td>$s = 0$</td>
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<tr>
<td>(2) Candle stick drill</td>
<td>$\alpha = 0$</td>
<td>$\alpha = \infty$</td>
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<tr>
<td>(3) Core drill</td>
<td>$\beta = 0, s = 0$</td>
<td>$\beta = 0$</td>
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4. EFFECTS OF PILOT HOLE [47]

A mathematical model of a plate subjected to symmetrical bending by thrust force of peripheral distribution with pilot hole ($F_{SP}$) is shown in Fig. 4.1 and Fig. 4.2. $b_r$ and $q$ are the radius of pilot hole and uniformly distributed load of intensity, respectively.

Fig. 4.1  Circular plate model for delamination analysis of a pre-drilled specimen
The thrust force of the saw drill with pilot hole at the onset of crack propagation as

$$F_{sp} = \pi \sqrt{\frac{32G_{IC}M}{1-4s^2+5s^4-2s^6-4s^2 \ln s + \frac{(1-\eta_s^2)s^2(1-s^2)(2\ln s + 1-s^2)}{[(1+\nu)\eta_s^2 + (1-\nu)]^2}}}$$

where \( \eta_s = b_p / c \). Eq. (4.1) indicates that the critical thrust force for specimens with pre-drilled pilot hole is a function of the ratio of the drill diameter to delamination diameter \((s)\) and the ratio of the pilot hole to drill diameter \( (\eta_s) \). In the Hocheng-Tsao model without a pilot hole for saw drill, the critical thrust force is given by Eq. (3.1) [18]. The theoretical critical thrust force of saw drill without pilot hole \((F_s)\) is found 38.8 N. To evaluate the effect of pilot holes on the critical thrust force value, the critical thrust force predicted by Eq. (4.1) was compared with that of Eq. (3.1) at various pilot hole ratio. Fig. 4.3 shows that the critical thrust force has little advantage up to \( s \approx 0.5 \), and the advantage of saw drill without pilot hole increases fast than saw drill with pilot hole with increasing \( s \).

Fig. 4.4 depicts the critical thrust force with respect to drill and delamination ratio for saw drill with various pilot hole ratio \((\eta_s)\). It is seen that the thrust force of saw drill with various ratio of pilot hole remains little different at \( s \geq 0.85 \), and has the effect below \( s = 0.85 \). Since the critical thrust force for saw drill with pilot hole is related to \( \eta_s \), the pre-drilled method is expected to be advantageous for allowing a larger critical thrust force at the onset of delamination. The smaller \( \eta_s \), the larger critical thrust force when \( s \) is below 0.85. Fig. 4.5 shows the variation of the critical thrust force for various Poisson’s ratio at \( \eta_s = 0.1 \). It is evident that the higher the Poisson’s ratio (larger \( \nu \)), the higher is the thrust force. The thrust force of saw drill with pre-drilled pilot hole remains little different at \( s \geq 0.85 \). The result indicates that \( \nu \) has a significant influence on the critical thrust force with pre-drilled pilot hole.
Fig. 4.3  Comparison of critical thrust force between Eq. (3.1) and Eq. (4.1) at various $\eta$

Fig. 4.4  Correlation between critical thrust force and drill and delamination ratio with various $\eta$
5. EFFECTS OF DRILL ECCENTRICITY

5.1 Eccentric Twist Drill [48]

Fig. 5.1 depicts an eccentric twist drill and the induced delamination, where $e$ is the chisel eccentricity in twist drill.

Fig. 5.1  Circular plate model for delamination analysis subject to eccentric twist drill

The critical thrust force ($F_{EA}$) at the onset of crack propagation can be derived.
\[ F_{EA} = \pi \frac{32G_{IC}M}{\sqrt{\left[1 + \frac{11}{4} \xi^2 + 7\xi^4 - 5\xi^2 \ln \xi + (1 + \xi^2)\xi^2 \ln^2 \xi\right]}} \]  

(5.1)

where \( \xi = e/a \).

The comparison of \( F_{EA} \) and \( F_A \) in Eq. (5.1) and Eq. (2.6) gives

\[ \frac{F_{EA}}{F_A} = \frac{1}{\sqrt{\left[1 + \frac{11}{4} \xi^2 + 7\xi^4 - 5\xi^2 \ln \xi + (1 + \xi^2)\xi^2 \ln^2 \xi\right]}} \]  

(5.2)

Fig. 5.2 depicts the ratio between the critical thrust force of eccentric twist drill and ideal twist drill varied with eccentricity ratio (\( \xi \)). The value of thrust force ratio decreases fast with increasing \( \xi \). In Fig. 5.2, the percentage of eccentricity of twist drill is nearly fully reflected in the percentage of the reduction of the critical thrust force. Namely the threshold thrust force beyond which delamination occurs is lowered, thus the drilling-induced damage becomes more liable. The eccentric twist drill allows for lower feed rate without delamination damage affecting productivity. The results agree with industrial experience. The quality control of tool regrinding significantly affects the drilling-induced damage. It explains the scattering hole quality in drilling composite materials. When the same nominal drill is used, the different drill eccentricity produced by tool regrinding causes the scattering.

5.2 Eccentric Candle Stick Drill [48]

Candle stick drill is extensively used for quality drilling of composite materials. Fig. 5.3 depicts the schematics of an eccentric candle stick drill and the induced delamination. The thrust force of the eccentric candle stick drill can be considered as a concentrated eccentric load (\( p_{e1} \)) plus the distributed circular load (\( p_{e2} \)).
Fig. 5.3  Circular plate model for delamination analysis subject to eccentric candle stick drill

The thrust force of the eccentric candle stick drill at the onset of crack propagation can be obtained.

\[
F_{EC} = \pi (1 + \alpha) \sqrt{\frac{32G_{ic}M}{\left[1 + \frac{11}{4} \xi^2 + 7\xi^4 - 5\xi^2 \ln \xi + (1 + \xi^2)\xi^2 \ln^2 \xi\right] + \alpha^2 (1 - 2s^2 + s^4)}}
\]  \hspace{1cm} (5.3)

where \(\alpha\) is the ratio of the concentrated eccentric force and the peripheral circular force.

The comparison of \(F_{EC}\) and \(F_A\) in Eq. (5.3) and Eq. (2.6) gives

\[
\frac{F_{EC}}{F_A} = \frac{(1 + \alpha)}{\sqrt{\left[1 + \frac{11}{4} \xi^2 + 7\xi^4 - 5\xi^2 \ln \xi + (1 + \xi^2)\xi^2 \ln^2 \xi\right] + \alpha^2 (1 - 2s^2 + s^4)}}
\]  \hspace{1cm} (5.4)

The candle stick drill exerts a thrust force on the laminate, which is composed of the concentrated central force and the peripheral circular force. When the delamination grows beyond the drill radius, the candle stick drill (applying the circular force and the concentrated force) can sustain much larger thrust force than the twist drill (applying the concentrated force), as shown in Fig. 5.4. When the eccentricity is zero, the value of force ratio larger than one illustrates this fact. Since the total thrust force is distributed toward the periphery at a ratio of \(\alpha\), the drill is expected to be advantageous in allowing for a larger critical thrust force, i.e. higher feed rate, at the onset of delamination. The results of the critical thrust force predicted by the eccentric candle stick drill are also presented in Fig. 5.4. It illustrates that the more the thrust force is distributed toward the periphery (larger \(\alpha\)), the larger becomes the critical threshold. This fact remains the same as the ideal candle stick drill. One notices in Fig. 5.4, the value of thrust force ratio decreases with increasing \(\xi\). It explains the serious effects of the incorrect tool reginding can lead to very scattering quality during drilling. The various degree of eccentricity of the same nominal drills will cause various degree of damage respectively.
5.3 Eccentric Saw Drill [49]

Fig. 5.5 depicts a deviation saw drill and the induced delamination, where $\delta$ is the deviation of the saw drill and $\theta$ is the ratio between deviation and radius of saw drill (namely, $\theta = \delta / c$).

The critical thrust force $F_{SD}$ at the onset of crack propagation can be calculated.

$$F_{SD} = \frac{\pi \sqrt{32G\mu M}}{1 - (1 - \theta)^2 \pi^2}$$  \hspace{1cm} (5.5)

The comparison of $F_{SD}$ and $F_s$ in Eq. (5.5) and Eq. (3.1) gives
Based on Eq. (5.5), the thrust factor \( Z \) is expressed by the ratio of the experimental thrust force \( F_{SD}^{\text{exp}} \) to the analytical thrust force \( F_{SD} \)

\[
Z = \frac{F_{SD}^{\text{exp}}}{F_{SD}}
\]  

Fig. 5.6 depicts the thrust factor of deviation saw drill with different drill diameters and crack sizes. One notices in Fig. 5.6(a), that \( \theta = 0 \) represents the ideal saw drill case. From Figs. 5.6(b) and 5.6(c), it can be seen that the deviation saw drill provides a relatively high thrust factor as compared with the ideal saw drill. According to DiPaolo et al., for the delamination size that is less than that of the drill is of no concern, because it would be drilled out afterwards [43]. When the delamination grows beyond the drill radius, the ideal saw drill could sustain a much larger thrust force than the eccentric saw drill. It demonstrates in the case of eccentric saw drill, that the less thrust force is distributed toward the periphery (smallest \( \theta \)), the larger the critical threshold becomes.
6. EFFECTS OF DRILL WEAR [50]

For a laminate subject to a uniformly distributed load and the worn chisel edge of twist drill (Fig. 6.1), the following analysis is available [42]. $a$ is the radius of circular plate and $b$ is the radius of the worn chisel edge on twist drill over a central circular area.

The critical thrust force $F_W$ at the onset of crack propagation can be calculated.

$$F_W = \pi \sqrt{\frac{32G_{IC}M}{1 - \frac{1}{2}\xi_w^2}}$$  \hspace{1cm} (6.1)

where $\xi_w = b/a$. The comparison of $F_W$ and $F_A$ in Eq. (6.1) and Eq. (2.6) gives

$$\frac{F_W}{F_A} = \frac{1}{\sqrt{1 - \frac{1}{2}\xi_w^2}}$$  \hspace{1cm} (6.2)

Fig. 6.1  Circular plate model for delamination analysis subject to worn twist drill
Based on Eq. (6.1), the thrust factor \( Z_w \) is expressed by the ratio of the experimental thrust force \( F_{\text{exp}} \) to the analytical threshold thrust force \( W_F \)

\[
Z_w = \frac{F_{\text{exp}}}{W_F} \tag{6.3}
\]

\( Z_w > 1 \) indicates the actual thrust during drilling is larger than the threshold thrust, hence the delamination is produced. The results of thrust factor at various tool-wear conditions are listed in Table 6.1. Fig. 6.2 depicts the correlation between the experimental thrust forces of worn twist drill varying with \( \xi_w \). Based on the experience, the tool wear is considered a major factor contributing to the thrust force. As illustrated in Fig.6.2 and Table 6.1, \( Z_w > 1 \) occurs throughout all the tested cases, it explicitly explains why the worn drill bit almost exclusively causes delamination damage during drilling, and a sharp and wear-resistant tool is desired.

![Graph showing correlation between thrust factor and tool wear](image)

Table 6.1  Thrust factor at various tool wear conditions

<table>
<thead>
<tr>
<th>Spindle speed (rpm)</th>
<th>Feed rate (mm/min)</th>
<th>Thrust factor ( Z_w ) (N/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>1000</td>
<td>10</td>
<td>58.4/34.19=1.71</td>
</tr>
<tr>
<td>1000</td>
<td>15</td>
<td>82.2/34.16=2.41</td>
</tr>
<tr>
<td>1000</td>
<td>20</td>
<td>101.6/34.15=2.98</td>
</tr>
<tr>
<td>1500</td>
<td>10</td>
<td>47.5/34.22=1.39</td>
</tr>
<tr>
<td>1500</td>
<td>15</td>
<td>71.3/34.18=2.09</td>
</tr>
<tr>
<td>1500</td>
<td>20</td>
<td>89.5/34.16=2.62</td>
</tr>
<tr>
<td>2000</td>
<td>10</td>
<td>37.6/34.30=1.10</td>
</tr>
<tr>
<td>2000</td>
<td>15</td>
<td>54.5/34.20=1.59</td>
</tr>
<tr>
<td>2000</td>
<td>20</td>
<td>68.2/34.18=2.00</td>
</tr>
<tr>
<td>Average</td>
<td>1.99</td>
<td>2.20</td>
</tr>
</tbody>
</table>
7. EFFECTS OF BACK-UP MATERIALS [23]
Delamination can be reduced by a support on the back of the workpiece, a commonly
followed practice in the industry. It is shown through finite element analysis that a serious surface
delamination is unlikely to happen when a back-up support is used [51].

7.1 Drilling with saw drill with back-up
Fig.7.1 depicts the center of the circular plate is supported under the workpiece with a saw
drill-induced delamination. In Fig. 7.1, \( F_{SF} \) is the upward reaction force from the backup plate
equal to the downward thrust force of the drill. The isotropic infinite plate behavior and pure
bending of the laminate are assumed in the model.

\[
F_{SF} = \frac{\pi}{2s^3 |\ln s|} \sqrt{32G_{ic}M}
\]

(7.1)

The critical thrust force \( F_{SF} \) at the onset of crack propagation can be calculated

The comparison of \( F_{SF} \) and \( F_s \) in Eq. (7.1) and Eq. (3.1) gives

\[
\frac{F_{SF}}{F_s} = \frac{\sqrt{1 - 2s^2 + s^4}}{2s^2 |\ln s|}
\]

(7.2)

A comparison of the theoretical critical thrust force of saw drill with and without backup as a
function of the drill diameter and the crack size is shown in Fig. 7.2. The thrust force of saw drill
with and without backup remains little different at \( s \geq 0.9 \) (i.e. the delamination size \( a \) is
close to the drill \( c \)). The thrust force of saw drill with backup increases fast with its maximum
at \( s = 0 \). \( s = 0 \) is the case approaching the use of twist drill that exerts a central point load on
the laminate. At \( s = 1 \), the drilling thrust is completely distributed to the periphery of the extent
delamination making it quite hard to propagate the crack. Hence the critical thrust force at the
onset of delamination growth approaches to theoretical infinite whether the backup is used to
support the laminate or not. The critical thrust force in use of the backup has a minimum at a
certain \( s \) between 0 and 1.
As pointed out by DiPaolo et al., the delamination of size less than the drill \((s > 1)\) is not of concern because it is drilled out afterwards anyway \([43]\). When the delamination grows beyond the drill radius, the saw drill with backup plate can sustain much larger thrust force than the saw drill without backup plate. Hence, the backup plate can offer higher feed rate to drill the composite materials without causing delamination. The result is in good agreement with the industrial experience.

![Graph showing critical thrust force ratio for saw drill with and without back-up](image)

**Fig. 7.2** Critical thrust force ratio for saw drill with and without back-up

### 7.2 Drilling with core drill with back-up

Fig. 7.3 depicts the center of the circular plate is supported under the workpiece with a core drill-induced delamination. In Fig. 7.3, \(F_{RF}\) is the upward reaction force from the back-up plate equal to the downward thrust force of the drill. The isotropic infinite plate behavior and pure bending of the laminate are assumed in the model.

![Diagram of circular plate model for delamination (core drill with back-up)](image)

**Fig. 7.3** Circular plate model for delamination (core drill with back-up)
The critical thrust force \( F_{RF} \) at the onset of crack propagation can be calculated

\[
F_{RF} = \pi \sqrt{\frac{32G_{IC}M}{(K_3 + K_4 + K_5 \ln s + K_6 \ln^2 s)s^4}} \tag{7.3}
\]

where

\[
K_3 = (2 - \beta)^2 \left[ -\frac{1}{4} (2 - 2\beta + \beta^2) \ln \frac{c(1 - \beta/2)}{a} - \frac{(1 - \beta)^4}{\beta(2 - \beta)} \ln(1 - \beta) \ln \frac{c(1 - \beta/2)}{a} \right] + (2 - 2\beta + \beta^2) \ln \frac{c(1 - \beta/2)}{a}
\]

\[
K_4 = -\frac{1}{2} (2 - 2\beta + \beta^2) + \frac{1}{16} (2 - 2\beta + \beta^2)^2 - \frac{(1 - \beta)^2}{\beta(2 - \beta)} (2 - 2\beta + \beta^2) \ln(1 - \beta)
\]

\[
K_5 = 2(2 - 2\beta + \beta^2) - \frac{1}{2} (2 - 2\beta + \beta^2)^2 + \frac{2(1 - \beta)^2}{\beta(2 - \beta)} (2 - 2\beta + \beta^2) \ln(1 - \beta)
\]

\[
K_6 = (2 - 2\beta + \beta^2)^2 + \frac{8(1 - \beta)^2}{\beta(2 - \beta)} (2 - 2\beta + \beta^2) \ln(1 - \beta)
\]

The comparison of \( F_{RF} \) and \( F_R \) in Eq.(7.3) and Eq.(3.5) gives

\[
\frac{F_{RF}}{F_R} = \sqrt{\frac{1 - K_1 s^2 + K_3 s^4}{(K_3 + K_4 + K_5 \ln s + K_6 \ln^2 s)s^4}} \tag{7.4}
\]

Fig. 7.4 shows the predicted critical thrust force for the core drill with and without backup. Fig. 7.4 indicates that for a given \( \beta \), the thrust force of a core drill with or without backup plate remains little different at large \( s \) (i.e. the drill is large compared with the delamination). This fact in the range of large \( s \) was discussed in the previous section of the saw drill case. The physics remains the same. As the \( s \) increases, the thrust force increases whether the backup is used or not. Fig. 7.4 illustrates the thrust force of core with backup is much higher than core drill without backup at small \( s \), where the delamination growth can be effectively counteracted by the support from the backup. The well known advantage of industrial practice of backup can be explained fundamentally by the fact that the threshold thrust force at the onset of delamination is increased making the delamination less likely to occur.
Drill Diameter to Delamination Diameter Ratio ($s = c / a$)

Critical Thrust Force Ratio $\pi \left( \frac{2G_{MC}}{1} \right)^{0.5}$

- core with backup plate $\beta = 0.1$
- core with backup plate $\beta = 0.3$
- core without backup plate $\beta = 0.1$
- core without backup plate $\beta = 0.3$

Fig. 7.4  Critical thrust force ratio for core drill with and without back-up

8. EFFECTS OF MATERIAL ANISOTROPY [34]

In the push-out model of Hocheng and Dharan [35], the property of composite materials is considered isotropic. The delamination front in the hole exit zone is a circle in shape. In fact, composite materials are inherently inhomogeneous and anisotropic in each layer. For a unidirectional composite laminate, Jain and Yang developed an anisotropic model for correlating thrust force with the onset of delamination [8]. The proposed shape of delamination is elliptical, with the long axis parallel to the fiber axis. For multidirectional composite laminates, drilling experiments have revealed that the shape of delamination is approximately elliptical [8]. The critical thrusts at onset of delamination for the isotropic and anisotropic material are as follows respectively. The comparison of results of isotropic and anisotropic analysis is shown in Table 8.1. When $k_{ani} = 1$, namely $a_{ani} = b_{ani}$, the anisotropic model reduces to orthotropic. The critical thrust force in the anisotropic analysis is a function of ellipticity ratio $k_{ani}$. The typical in-plane lamina stiffness properties and interlaminar fracture energy of composite materials are shown in Table 8.2. Fig. 8.1 shows a plot of $E_{11}^* A_{AA} / E_{11}^* A_{II}$ against $k_{ani}$ for three different epoxy-matrix materials. The minimum critical thrust force corresponds to a value of $k_{ani} = \frac{a_{ani}}{b_{ani}} = \left( \frac{D_{11}}{D_{22}} \right)^{1/4} = \left( \frac{E_{11}}{E_{22}} \right)^{1/4}$. For the commonly used unidirectional fiber-reinforced material, the observed value of $k_{ani}$ lies between 1 and 2, consequently the critical thrust force is reduced by about 20% to 40%. In the often employed 0/90-woven material, the value moves closer to 1. Among the three materials, the E-glass/epoxy offers the highest thrust force closest to the isotropic case followed by the AS4/3501-6, while the T300/5280 allows for the lowest thrust force ratio. This fact is partially attributed to the closest ratio of $\frac{E_{11}}{E_{22}}$ of E-glass/epoxy among three materials.
Table 8.1 Comparison of isotropic and anisotropic analysis

<table>
<thead>
<tr>
<th>Point / Circle [35]</th>
<th>Point / Elliptic [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X = \frac{F_A a^2}{16\pi M}$</td>
<td>$X = \frac{F_A k_{ani} a_{ani}^2}{6\pi D^*} = \frac{F_A k_{ani} a_{ani}^2}{6\pi \cdot \frac{8}{3} M} = \frac{F_A a_{ani}^2}{16\pi M}$</td>
</tr>
<tr>
<td>$U = \frac{8\pi M X^2}{a^2} = \frac{F_A a^2}{32\pi M}$</td>
<td>$U = \frac{4\pi b_{ani}^2 D_{11} + 2/3(D_{12} + 2D_{66}) k^4 + D_{22} k^4}{a_{ani}^3}$</td>
</tr>
<tr>
<td>$= \frac{4\pi b_{ani}^2 F_A^2 k_{ani}^2 a_{ani}^4}{256\pi^2 M^2} = \frac{F_A^2 a_{ani}^2}{32\pi M}$</td>
<td>$= \frac{3\pi}{k_{ani}^2} \sqrt{2G IC D^7}$</td>
</tr>
</tbody>
</table>

where
- $a$ is radius of the circle delamination.
- $a_{ani}$ is half major axis length of the elliptical delamination.
- $b_{ani}$ is half minor axis length of the elliptical delamination.
- $k_{ani} = \frac{a_{ani}}{b_{ani}}$ is the ellipticity ratio.
- $D^* = D_{11} + 2/3(D_{12} + 2D_{66}) k_{ani}^2 + D_{22} k_{ani}^4$. 

Fig. 8.1 Critical thrust force versus ellipticity ratio for three different epoxy-matrix materials
$D_{11}$, $D_{12}$, $D_{22}$ and $D_{66}$ are bending stiffnesses.

Table 8.2 Typical in-plane lamina stiffness properties and interlaminar fracture energy of composite materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_{11}$ (Gpa)</th>
<th>$E_{22}$ (Gpa)</th>
<th>$v_{12}$</th>
<th>$G_{12}$ (Gpa)</th>
<th>$G_{IC}$ (J/m$^2$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS4/3501-6</td>
<td>131.0</td>
<td>11.2</td>
<td>0.28</td>
<td>6.55</td>
<td>136</td>
<td>[52-55]</td>
</tr>
<tr>
<td>T300/5208</td>
<td>153.0</td>
<td>11.2</td>
<td>0.33</td>
<td>7.1</td>
<td>88</td>
<td>[56-57]</td>
</tr>
<tr>
<td>E-glass/epoxy</td>
<td>38.6</td>
<td>8.27</td>
<td>0.26</td>
<td>4.14</td>
<td>207</td>
<td>[58-59]</td>
</tr>
</tbody>
</table>

9. MEASUREMENT OF DELAMINATION [60]

To determine the extent of drilling delamination area produced by twist drill, two nondestructive evaluation (NDE) methods were studied. The specimens were examined using ultrasonic C-Scan and computerized tomography (CT). With X or $\gamma$-ray CT, the intensity of a collimate X or $\gamma$-ray beam passing through an object is measured by an array of detectors located opposite to the X or $\gamma$-ray source. It is proposed a feasible and an effective tool for the evaluation of drilling-induced delamination in the current study.

9.1 Ultrasonic C-Scan

Ultrasonic C-Scan utilizes the sound energy at frequencies above 20 kHz to detect the defect of specimen. When an ultrasonic wave reaches an interface or a discontinuity, a portion of the energy is reflected. The amount of reflected energy depends on the specific acoustic impedance of each media, which is the product of the velocity, of the ultrasonic wave in the medium and the density of the medium. The energy transmitted through the material is reduced due to the energy reflection and attenuation within the specimen. Thus, the variations in reflected and/or transmitted energy can serve as means for locating defects (discontinuities) in the path of the ultrasonic wave.

In fact, a pulse generator transmits an electrical pulse through a coaxial cable to a transducer, generally a piezoelectric device, which converts the electrical pulse to mechanical energy. The mechanical energy is then fed into the specimen using a coupling medium - water. A transducer picks up the sound energy reflected by or transmitted through the specimen, and converts the sound to electrical energy. The results are then analyzed and displayed on the cathode ray tube (CRT).

Two types of ultrasonic NDE method were applied to composite materials. One is the pulse-echo method, and the other is through-transmission method (C-Scan). The pulse-echo method of ultrasonic NDE utilizes the ultrasonic energy reflected from a discontinuity for locating defects. A defect is determined to be present if energy is reflected prior to reaching the back surface. From the CRT, one can observe a peak between those pulses corresponding to the initial pulse and the back-surface reflection. The location of the defect can be estimated based on the relative position of the resulting peak with respect to the initial pulse and back-surface reflection peaks.

In through-transmission, the ultrasonic energy is measured after it passes through the material. Both surfaces must be accessible to the transducers. Reduction of energy due to a defect results in reduced amplitude of the peak on the CRT. The schematic of ultrasonic C-Scan is shown in Fig. 9.1. Through-transmission, if practical, is generally preferred for thicker parts.

Both techniques have been found satisfactory for locating delaminations that are large in size.
and located perpendicular to the direction of ultrasonic transmission. Small delaminations or voids, resin-starved areas, and porosity are more difficult to detect. Through-transmission is preferred in this study, utilizing the attenuation of the ultrasonic wave due to the presence of such defects. Pulse-echo may be used provided the part is not too thick, so that excessive attenuation results are found for defect-free parts.

The ultrasonic C-Scan test was made on an AIT-5112 (Automated Inspection Technologies Inc.) unit. The specimen was placed between the sender and receiver. When the sender emits ultrasonic wave, the attenuation through the receiver is recorded in computer. The schematic of X-ray computed tomography Techniques is shown in Fig. 9.2. In computed tomography, X or γ-rays from a finely collimated source deals with the cross-sectional imaging of an object from either transmission or reflection data are collected by illuminating a slice of the object or patient from many different directions. Basically a CT scanner consists of an X or γ-ray source from which an X or γ-ray beam is transmitted through an object and is detected, manipulated electronically, and stored in a computer. These transmitted radiation beams have a modulated intensity dependent on the overall linear attenuation characteristics of the intervening material. This modulated or varying intensity with respect to distance is referred to as a profile. This profile information is then manipulated to produce a reconstructed image of an object. The reconstructed image is then displayed on a viewing monitor for evaluation and interpretation.
9.2 Computerized Tomography (CT)

X-ray computerized tomography (CT) has been very useful in medical diagnosis since the first commercial tomographs were constructed in 1973. The capacity of this technique to show sample cross-section in a non-destructive way also made it appreciable in industry. In the set-up, as shown in Fig. 9.3, a narrow beam of X-rays scans the object. The X-ray tube, detectors and collimators are fixed to a common frame. Those rays which pass through the specimen are detected by two collimated sensing devices which always point towards the X-ray source. Recent advances in X or γ-ray technologies have allowed development of computed tomography methods for rapid, non-destructive, three-dimensional (3D) analysis of intact biological tissue [61]. In computed tomography, X or γ-rays from a finely collimated source deals with the cross-sectional imaging of an object from either transmission or reflection data are collected by illuminating a slice of the object or patient from many different directions. Basically a CT scanner consists of an X or γ-ray source from which an X or γ-ray beam is transmitted through an object and is detected, manipulated electronically, and stored in a computer (Fig. 9.2). These transmitted radiation beams have a modulated intensity dependent on the overall linear attenuation characteristics of the intervening material. This modulated or varying intensity with respect to distance is referred to a profile. This profile information is then manipulated to produce a reconstructed image, which is then displayed on a viewing monitor for evaluation and interpretation.

The computer tomography for the carbon fiber-reinforced composites was made by means of the Siemens Somatom AR high performance X-ray medical computer tomography provided with an MCT141 CT X-ray tube, of which the acceleration potential can be selected between 110 and 130 kV. By CT, it is possible to determine the damage through the thickness of the laminate. During one scan, the specimen is irradiated with X-rays. A detector on the opposite side detects the attenuation caused by the object and converts the signal to an optical image, which is recorded with a video camera. The X-ray is rotated incrementally 180° around the axis perpendicular to the specimen feed direction. The scan is then visualized on a computer screen, which shows a slice of the specimen perpendicular to the direction of the X-rays. The schematic of X-ray computed tomography of the attenuation and detection of radiation is shown in Fig. 9.2. The image reconstruction was performed by a FUJIX Medical Image Processor MF-300S, which ensures fast reconstruction within 6-14 second. The reconstructed images were displayed on a high definition monitor, from which they were copied on a film. All the images presented in this
report are positive copies on photographic paper obtained from the negatives.

To illustrate the fine delamination area of the carbon fiber-reinforced composites, the serial CT slides were taken by optimal window width and center. These pictures correlate the X-ray absorption density to the mechanical density of the sample. The intrinsic X-ray absorption density scale of the CT is in Housfield units (HU).

In Fig. 9.4, the ultrasonic C-Scan and CT scan of the extent of the drilling defects (delamination) are presented. Around the hole in the specimen, the damage was evident from the edge of the hole. Though the delamination is a very common defect during drilling, the study on the radiological evaluation is rare. From Fig. 9.4, the shape of delamination at two cutting conditions was found slightly different. Higher feed rates produce not only larger delamination, but also more irregular shape of delamination. From the aspect of energy balance, high feed rates exert large thrust force and do more work on the specimen as drilling proceeds. This energy is partially stored as strain energy and also partially consumed in larger extent of delamination during drilling. Hence a positive relationship between thrust force and delamination area is expected, as shown in Fig. 9.5.

Based on the analytical push-out model [35], the critical thrust force of twist drill calculated by Eq. (2.6) is \( F_A = 66.5\, N \). The ultrasonic C-Scan and CT show the experimentally measured value to be 63.7\( \, N \) and 62.5\( \, N \), respectively, as shown in Table 9.1. It can be seen that the measured results by C-Scan and CT agree well with the analysis above. Fig. 9.5 and Table 9.1 illustrate that CT is an effective tool comparable to C-Scan for the evaluation of delamination in composite materials and finding the critical thrust force.
10. CONCLUSION

A comprehensive analysis of the drilling-induced delamination for composite laminates in use of twist drill, saw drill, candle stick drill, core drill, step drill and other composite drills is developed in the present study. The analytical results are obtained based on linear elasticity, fracture mechanics and energy conservation. This study also presents the experimental results of the drilling-induced delamination in use of special drills. The results are found consistent with the theoretical predictions of critical thrust force at the onset of delamination. Due to the different drill geometry, these drills show different level of drilling thrust force varying with the feed rate. Among the five drills, the core drill offers the highest critical feed rate followed by the candle stick drill, saw drill and step drill, while the traditional twist drill allows for the lowest feed rate. In other words, the core drill, candle stick drill, saw drill and step drill can be operated at larger feed rate or in shorter cycle time without delamination damage compared to the twist drill. The results agree with the industrial experience, that the former drills cause less delamination during
Their advantageous drill design is explained based on the derived models that illustrate their thrust force exerted by drill is distributed toward the drill periphery rather than concentrated at hole center. This approach can be extended to examine the effects of other special drills or the future innovative drill design.

References


