Computerized Tomography and C-scan for Measuring Drilling-Induced Delamination in Composite Material Using Twist Drill and Core Drill

H. Hocheng¹,a and C.C. Tsao ²,b
⁰Department of Power Mechanical Engineering, National Tsinghua University, Taiwan
¹Department of Automatic Engineering, Tahua College of Technology, Taiwan
a,hocheng@pme.nthu.edu.tw,  b,aetcc@msdb.thit.edu.tw

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Abstract. Delamination is one of the most concern defects in drilling of composite material. Delamination depends on the factors such as feed rate, tool geometry and wear. The mechanics of drilling composite materials has been examined along with the quality of the hole and the effect of tool design parameters. The capacity of computerized tomography (CT) showing sample cross-section in a nondestructive way made it successful in measuring the drilling-induced delamination. In the experiment, the correlation between thrust force and the measured delamination extent in use of twist drill and core drill is illustrated and compared with the known ultrasonic C-scan. It is compared with the ultrasonic technique and is demonstrated a feasible and an effective tool for the evaluation of drilling-induced delamination.

Introduction

The mechanical properties of composite materials are well recognized as a different from that of metal for their high specific strength, high specific stiffness and corrosion resistance. In composites, due to the inherent nonhomogenerous and orthotropic nature of the material, the characteristic of machining is different from that of homogeneous metal removal [1]. Failure mechanisms of composite materials are quite complex in machining. Delamination is one of the most concern defects in drilling of composite material. Delamination varies from depending on several factors such as feed rate, tool geometry and wear [1-5]. The mechanics of drilling composite materials has been examined along with the quality of the hole and the effect of tool design parameters. It is well known that drill point geometry has a significant effect of the thrust force of a twist drill [6-8]. Many types of drill bits have been tested on glass-epoxy laminates [9]. Koenig et al. investigated the effect of drilling thrust on delamination damage [1,10]. The point geometry of the multifacet drill (MFD) has the obvious advantages in reducing thrust force and in distributing the cutting temperature. Wu used multifaceted drills to reduce the thrust force up to 70 percent as compared with a conventional twist drill has been achieved [11]. Haggerty and Ernst found that “spiral” point drills performed much better than the conventional ones [12]. Ko et al. used a step drill to minimize the burr size in drilling [13]. Jain and Yang designed a hollow grinding drill and tested [14]. This tool resulted in a much smaller thrust and much better hole quality compared with the twist drill. Delamination at the exit side can be improved if the drilling-induced thrust is distributed to circular load. The saw drill, candle stick drill, core drill and step drill have the merit of a better distributed circular load than twist drill [15].

Delamination in drilling processing was usually investigated by ultrasonic C-scan [16-17]. Generally, due to the heterogeneity of composite material, conventional C-scan is unable to provide information regarding the details of damage. The normal practice in evaluation of delamination through ultrasonic C-scan is to obtain a projected area. However, delamination at various interfaces distributed through the thickness. The capacity of CT showing sample cross-section in a nondestructive way made it successful in industry. There are few works using computerized tomography for the evaluation of delamination produced by drilling. It is proposed a feasible and effective tool for the evaluation of drilling-induced delamination extent in the current study. In the
experiment, the correlation between thrust force and the measured delamination in use of twist drill and core drill are illustrated and compared with the known ultrasonic C-scan.

**Experimental Setup**

The carbon/epoxy composite materials for drilling 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 made the plate thickness 3.6 mm. The fiber volume fraction is 0.63, the modulus of elasticity \((E)\) is 189 Gpa, the energy release rate \((G_{IC})\) is 240 J/m², and Poisson’s ratio \((\nu)\) is 0.3.

The twist drills of 10 mm diameter with high speed steel was used. The diameter of the core drill is 10 mm with one end of the tube coated with diamond and its length and thickness are 12 mm and 1 mm, respectively. Drilling tests were carried out on a LEADWELL MCV-610AP vertical machining center. The mean thrust forces at the exit of the drill bits during drilling were measured with a Kistler 9273 piezoelectric dynamometer. Meanwhile, the drilling and thrust forces signals were transmitted to Kistler 5019 charge amplifiers and stored in a TEAC DR-F1 digital recorder subsequently. The amplifier has to stabilize for at least an hour. All tests were run with coolant at spindle speed of 900 and 1000 rpm and feed rates of 10, 11 and 12 mm/min, respectively.

**Nondestructive Evaluation Methods**

In X-ray computed tomography, a beam of radiation passes through the object and exposes a film in a light-tight packet. The resulting image is a high resolution projection of the object. Computed tomography is the reconstruction of a cross-sectional image of an object from its X-ray projection. In other words, it is a coherent superposition of projections obtained using a scanner to reconstruct a pictorial representation of the object. The schematic of X-ray computed tomography is shown in Fig. 1. 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. The X-ray is rotated incrementally 180° around the axis perpendicular to the specimen feed direction. The schematic of X-ray computed tomography of the attenuation and detection of radiation is shown in Fig. 1. To illustrate the fine delamination 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.

![Fig. 1 Schematic of X-ray computed tomography](image1)

![Fig. 2 Schematic of ultrasonic C-scan](image2)

The schematic of ultrasonic C-scan is shown in Fig. 2. The ultrasonic C-scan test was made on an AIT-5112 unit. The three axes of motion consist of a 0.025 mm resolution scanning bridge by add on cards control the mechanical motion and an AIT-2230 ultrasonic pulser/receiver and digital oscilloscope. The software AcouLab is used to program the scan cycle, acquire/display data, carry out data processing and produce a 2-D data display. The transducer (9.5 mm in diameter) with a...
center frequency of 5 MHz is the type of the immersion. The specimen was immersed in the water tank and the probe was brought on to the specimen. For data acquisition, different ultrasonic parameters, such as damping, attenuation, gate, threshold, delay, blanking, gain, pulse amplitude, pulse width and pulse repetition rate, are accessed and correctly set. As it was aimed to scan the specimen layerwise, the probe emits ultrasonic wave while the attenuation through the receiver is recorded at each point, stored in the internal buffer of the oscilloscope and transferred to the computer hard disk. Selecting the appropriate gate location and width, the delamination of the specimen is reconstruct. Though the delamination is a very common defect during drilling, the study on the radiological evaluation is rare. The present study aims at a comparison between the computerized tomography (CT) scan and ultrasonic C-scan findings.

A software program was developed using image processing techniques, which extracted ultrasonic image data like length and width during scanning along the two axes. This information is used to calculate the delamination. Each delamination image indicated the differences in laminates density by an array of gray scale values (0-255). The pixel value of the center drilled hole is set to 0 (black) when it is less than the threshold value; the delamination zone is meanwhile set to 255 (white). The proper threshold value was determined by the histogram of array values and verified by the original and binary images. The extent of delamination was an average taken from six measurements along the circumstance of the delamination.

**Experimental Threshold Drilling Thrust**

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 delamination during drilling. Hence a positive relationship between thrust force and delamination is expected, as shown in Fig. 3.

![Experimental correlation between thrust force and delamination for twist drill and core drill](image-url)

Fig. 3 Experimental correlation between thrust force and delamination for twist drill and core drill

The delamination photograph from the ultrasonic C-scan and CT is shown in Fig. 4. In Fig. 4, the CT results of the drilling defects (delamination) are presented. Around the hole in the specimen, the damage is identified extended from the edge of the hole. At low feed rate, the delamination is small.
The delamination is enlarged with increasing feed rate. The results agree with early reference of drilling delamination. The experimental correlation between the drilling thrust force and the extent of delamination is reported [1,10]. The shape of delamination at two cutting conditions is found slightly different.

Fig. 4 Ultrasonic C-scan and CT scan show the extent of drilling-induced delamination for twist drill and core drill (spindle speed = 1000 rpm, feed = 0.012 mm/rev)

Based on the analytical push-out model [15,18], the critical thrust force of twist drill and core drill at onset of drilling-induced delamination are

\[
F_A = \pi \sqrt{\frac{32 G_h M}{8 G_h E h}}^{1/2}
\]

\[
F_R = \pi \left[ \frac{32 G_h M}{1 - [(2 - 2 \beta + \frac{3 \beta^2}{2}) + \frac{4(1 - \beta^2) \ln(1 - \beta)}{\beta(2 - \beta)} \frac{32 G_h M}{2}} + \frac{(2 - 4 \beta^2 + 5 \beta^3 - 3 \beta^4 + \beta^5)}{\beta(2 - \beta)} \frac{32 G_h M}{2}}\right]^{1/2}
\]

where \( M \) is flexural rigidity of the plate, \( E \) is the modulus of elasticity, \( G_{IC} \) is the energy release rate, \( h \) is the uncut depth under tool, \( \nu \) is the Poisson’s ratio. \( F_A \) and \( F_R \) are the thrust force of twist drill and core drill, respectively. \( \beta \) is the ratio between thickness (\( t \)) and radius of core drill (\( c \)) (namely, \( \beta = t / c \)). The critical thrust force calculated by Eqs. (1) and (2) are \( F_A = 66.5 \text{N} \) and \( F_R = 80.4 \text{N} \), respectively. The ultrasonic C-scan and CT show the experimentally measured value as shown in Table 1. Fig. 4 and Table 1 illustrate that CT is an effective tool compared with C-scan for the evaluation of delamination in composite materials. In Table 1, the error of core drill is higher than twist drill. The facts can be attributed to the following two aspects. The grit size of diamond is corrected with the thrust force for core drill. On the other hand, the heat caused by the core drill in drilling melt the matrix of composite material decrease the thrust force in the mathematic analysis, when dry machining is employed.

Table. 1 Comparison of C-scan and CT for critical thrust force of twist drill and core drill (spindle speed = 1000 rpm, feed = 0.012 mm/rev)

<table>
<thead>
<tr>
<th>Drill bit</th>
<th>Theoretical critical thrust force (N)</th>
<th>Experimental critical thrust force (N) obtained by CT</th>
<th>Experimental critical thrust force (N) obtained by C-scan</th>
<th>ABS. error of CT (%)</th>
<th>ABS. error of C-scan (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twist drill</td>
<td>66.5</td>
<td>60.4</td>
<td>64.3</td>
<td>9.2</td>
<td>3.3</td>
</tr>
<tr>
<td>Core drill</td>
<td>80.4</td>
<td>63.8</td>
<td>70.2</td>
<td>20.6</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Conclusions

This paper presents the drilling-induced delamination of composite materials can be visualized and measured by the ultrasonic C-scan as well as the X-ray computerized tomography. The obtained results show that both ultrasonic C-scan and CT perform similarly (within 21 %). Both can reveal...
experimentally the critical thrust force at the onset of delamination. Hence, CT is demonstrated as a feasible and an effective tool for the evaluation of drilling-induced delamination. On the other hand, the reported correlation between the thrust force and delamination, as well as the proportionality between feed rate and delamination, can be recognized by the proposed technique.

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References

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