Composite Structures 139 (2016) 36–41

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Utilizing internal icing force to reduce delamination in drilling composite tubes

H. Hocheng [a,*], C.C. Tsao [b], H.T. Chen [a]

[a] Department of Power Mechanical Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan, ROC
[b] Department of Mechatronics Engineering, Ta Hua Institute of Technology, Hsinchu 30740, Taiwan, ROC

ARTICLE INFO

Article history:
Available online 30 November 2015

Keywords:
Composites
Drilling
Delamination
Tube
Icing
Bach-up

ABSTRACT

Thanks to the superior mechanical properties and corrosion resistance, composite materials have been increasingly utilized in industries over the past decades. Drilling is indispensable for building load-carrying structure of composites. Owing to the peculiar property of composite laminates, delamination defect is often produced at the exit of drilling, which leads to serious concerns of reliability and safety. This research presents an innovative method of utilizing the internal expansive force during water icing to suppress delamination in drilling on wall of composites tubes. The experimental results demonstrate the delamination extent can be reduced by 40% on average, while the drilling feed rates can be elevated more than 400% when maintaining the same level of delamination extent. The effects are enhanced with increasing feed rates. Being more advantageous than the previous method of applying electromagnetic media inside the tube as back-up, the water icing is both clean and easily remolten as well as recycled leaving little environmental concerns after use. It requires no attention of cleaning the drill bit. The proposed innovative method is effective and inexpensive for industry.

1. Introduction

Composite materials have grown rapidly as the structural parts in many industrial sectors ranging from the advanced aerospace to electrical vehicles and leisure goods. The composite materials possess superior mechanical properties of high levels of strength-to-weight ratio, fracture toughness, corrosion resistance and abilities for adapting to a variety of shapes to meet the applications. An example is the electrical car-BMW i3 launched in 2013, the vehicle frame is built of 100% carbon fiber-composites. Such an application demonstrates more than 30% reduction on weight in contrast to the conventional steel frames [1]. The composite tubes have gained more extensive applications including the frame structure for aerospace and the high-end bikes and sporting goods. For the whole structural frame, the tubes can offer higher strength-to-weight ratio thanks to the hollow shape, while the structural assembly cycle time can be shorter.

Drilling is the most frequent and economically adopted machining process, amongst all hole-making operations, to produce bolted and riveted joints for parts assembly. Nevertheless, the defects and damages often occurred during the drilling processes including delamination, microcracking and burr. The drilling-induced delamination, considered the most serious concern, is found at the exit side around the hole edge which lowers the bearing strength of joints, shortens its service life and threatens safety in applications [2,3].

The thrust force of drilling is identified as the primary factor of drilling-induced delamination and researchers have conducted extensive studies. A physical model of drill bits and laminates during drilling was constructed, based on which the critical thrust force was derived, below this critical value no delamination occurs [4]. The increasing thrust force of drilling leads to enlarged delamination area. In consideration of the direct relationship between the feed rate and thrust force, a strategy for dealing with machining of composites is suggested [5]. The thrust force was captured and a third order transfer function between thrust force and feed rate was identified by Matlab further converted into state-space model [6]. The effects of feed rate, eccentricity and various geometries of drill bits are investigated to improve the machining quality [7–9]. A three-dimensional finite element simulation of drilling process is found an effective method in optimizing the drill geometry and process parameters in order to improve hole quality and to predict delamination [10,11]. The critical thrust force for thick and stacked material structure of composites was also investigated [12,13]. For inspecting the drilling defects such as delamination, the ultrasonic C-Scan is widely adopted. The computerized

* Corresponding author.

http://dx.doi.org/10.1016/j.compstruct.2015.11.043
0263-8223/

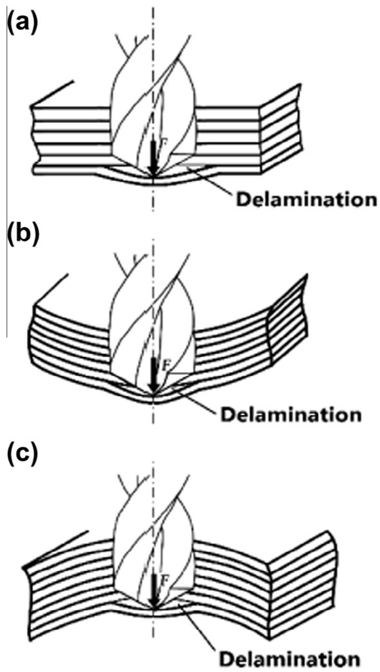

Fig. 1. Drilling composite and delamination (a) on a flat plate (b) on a curved plate along curvature (c) on a curved plate against curvature [17].

tomography (CT) is demonstrated a feasible method for accurate measurement of the delamination extent at higher cost [14].

How to reduce the drilling-induced delamination with optimal drilling parameters remains an essential issue in industries. The industrial practice often utilizes a back-up plate under the drilled parts for reducing the delamination. The analysis based on the afore-mentioned model explains the effects are attributed to the increased level of the critical thrust force when the back-up plate provides a counter force in opposite direction, which leads to the reduced delamination extent [15]. The use of pilot-hole is also shown as a method to reduce the delamination extent for the thrust force can be significantly decreased is practice [16].

Though several approaches for reducing the delamination have been proposed for drilling of flat-plates, few were reported for the parts with curvatures, such as the tubes. Fig. 1 shows the configurations in drilling curved parts, namely along or against the curvature, in which drilling against the curvature presents higher level of delamination due to the buckling effects at the exit laminae. Less strain energy is needed to generate the delamination crack. Drilling the tube wall from outside belongs to this category. An electromagnetic device can be installed on the tube to attract the iron colloid inside producing a magnetic force outward as a back-up against the thrust from outside [17]. The results show the good effects of reducing the delamination area. However, this approach is born with the concerns, including the time-consuming packing and unloading of the electromagnetic colloid, the viscous colloid being left on the drill bit through drilling, and some over-sized tubes not fit to the common electromagnet devices.

This paper describes an innovative method of employing the basic principle of the water expansion when getting frozen. Hence the expansive icing force inside the composites tubes is utilized as the back-up force against delamination in drilling the tube wall from outside. The schematic of the concept is shown in Fig. 2. The good flowing ability of water warrants easy filling and unloading with the tubes in operations, and the material and equipment are cost effective.

2. Analysis of expansion back-up from internal icing

The extent of delamination is found increasing with the drilling thrust [2,3]. On the other hand, the application of back-up has been proved effective for reducing the delamination [15]. The core of the current research is to utilize the internal icing force as the back-up. The theoretical analysis is focused on how much expansive back-up force can be produced during freezing process.

The internal expansive pressure can be estimated based on the mechanics of material by two approaches. One is to calculate directly the theoretical thermal stress acting against the inner wall of tube during water icing. The other approach is to calculate the expansive pressure through the hoop stress on the tube, which is obtained experimentally in use of the measured strains on the external surface during expansion of the tube as a result of water icing inside tube.

2.1. Theoretical thermal stress during icing expansion in tube

The thermal stress is expressed as

$$\sigma_\theta = \alpha \times \nabla T \times E \qquad (1)$$

where α is the coefficient of thermal expansion of water, which is $-159 \times 10^{-6}\ \mathrm{K}^{-1}$, ∇T is the change of temperature, namely $-20\ ^\circ\mathrm{C}$, and E is the Young's modulus of ice, which is 12×10^9 Pa [18]. The substitution of these values into Eq. (1) yields

$$\sigma_\theta = -159 \times 10^{-6} \times (-20) \times 12 \times 10^9 = 38.16\ \mathrm{MPa} \qquad (2)$$

The thermal stress is regarded as the radial pressure, P_{int}, as shown in Fig. 3. The back-up force, F_B, acting on inner surface against the drilled area can be calculated, equals to the internal pressure multiplied by the drilled area which is considered nearly a planar round area

$$F_B = \left(\frac{\emptyset}{2}\right)^2 \times \pi \times P_{int} = \left(\frac{2}{2}\right)^2 \times \pi \times 38.16\ \mathrm{MPa} = 119.89\ \mathrm{N} \qquad (3)$$

where $\emptyset$ is the diameter of drill bit, 2 mm in the current study.

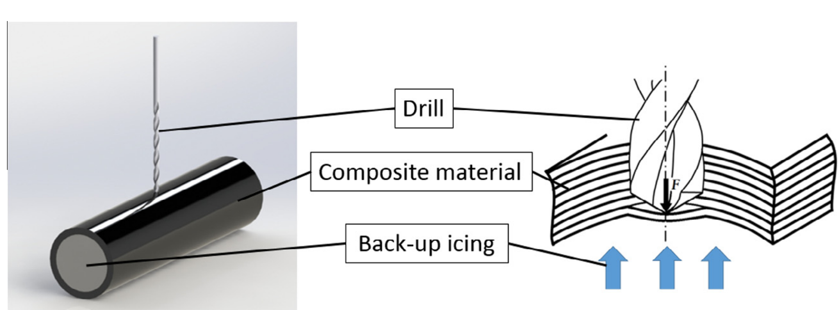

Fig. 2. Applying internal icing as back-up in drilling tube wall.