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Effect of the drilling process on the compression behavior of glass/epoxy laminates

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ABSTRACT

Composite materials have been widely used in various industries due to their superior mechanical properties. Drilling is a very common machining operation to install fasteners for assembly of laminates. Delamination, however, is a serious concern in the drilling of fiber reinforced composite materials, because it reduces their compressive residual strength. This paper studies the effects of drilling parameters on the thrust force, adjusted delamination factor and compressive residual strength of uni-directional glass/epoxy resin. The design of the experiment was based on the Taguchi method. The results highlight the importance of the feed rate for maximizing the compressive residual strength of drilled laminates. The Acoustic Emission (AE) technique was also used to monitor both drilling process and compression test. The objective was to establish a correlation between AE parameters and mechanical characteristics. The results reveal that root mean square (RMS) can be used for monitoring thrust force and AE energy for compression force.

1. Introduction

1.1. Drilling of composite materials

The field of composite materials has progressed considerably over the last few decades, as shown by the widespread use of fibrous composite materials for airframes, automobile components, sporting goods and other lightweight structures. Low density, high strength and stiffness, chemical and corrosion resistance, etc. make composite materials an attractive alternative to metals and alloys. Current challenges in the field of composite materials are associated with the improvement of composite materials through manufacturing. The composite materials are primarily fabricated by processes such as hand lay-up, filament winding, autoclave curing, etc. Machining operations are then performed to produce the finished components and structures.

Making holes is one of the main machining operations performed to assemble the sub-components during the processing stages. Among all the approaches used for making holes in composite laminates, conventional drilling (using twist drills) is the most simple and widely acceptable machining operation. In drilling composite parts, the mechanism of machining has been recognized as a process different from that of homogeneous and isotropic metal removal of conventional materials. Several forms of damage occur during drilling. Among them, matrix cracking, fiber pull-out, fiber breakage and delamination are the most significant. The major damage is certainly delamination, defined as the separation of the layers of materials in a laminate. This occurs due to localized bending in the zone sited at the point of drill contact. Drilling-induced delamination occurs both at the entrance (peel-up) and the exit sides of the work piece. The delamination on the exit side, referred to as push-down, is considered the most crucial. Chen [1] proposed an approach to obtain the values of conventional delamination factor expressed by the following equation:

$$F_d = \frac{D_{max}}{D_0} \quad (1)$$

where D_0 is the nominal diameter of the hole (or drill bit) and D_{max} is the maximum diameter of the damage hole.

A novel approach was proposed by Davim et al. [2] to obtain the values of adjusted delamination factor expressed as Eq. (2). The first part of Eq. (2) represents the size of crack contribution and the second part represents the damage area contribution.

$$F_{da} = \alpha\frac{D_{max}}{D_0} + \beta\frac{A_{max}}{A_0} \quad (2)$$

where A_0 and A_{max} are the areas related to the nominal hole and maximum diameter of the delamination zone respectively. The coefficients α and β can be calculated from the following equation:

$$\beta = \frac{A_d}{A_0 - A_{max}} \quad \text{and} \quad \alpha = 1 - \beta \quad (3)$$

where A_d is the delaminated area.

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Many papers have been published on the drilling of composite materials using analytical and numerical approaches. Lachaud et al. [3] proposed a model which links the axial penetration of the drill bit to the conditions of delamination (crack opening mode I) of the last few plies. Their results showed a close correlation between experiment and calculation; when the thrust force of the drill was modeled by taking into account the geometrical nature of the contact between the tool and a laminate composite material. Tsao et al. [4] studied the effect of active backup force on delamination in drilling composite materials. A comprehensive analysis of the critical thrust force without and with the active backup force in the drilling of composite materials was presented. Their results revealed that the critical thrust force with the active backup force can be significantly elevated compared to those without backup. Zitoune et al. [5] used a numerical FE analysis to predict the thrust force responsible for the damage at the exit of the hole during the drilling phase of long-fiber composite structures. According to their results, a good correlation had been noticed between the numerically calculated efforts and those which were experimentally obtained. Dura~o et al. [6] used the finite element model in order to simulate thrust force and delamination onset during drilling. They compared the thrust-displacement curve and the one obtained in the experimental work and reported that a good agreement between numerical and experimental thrust curves was obtained.

1.2. Dynamic analysis of drilling process

For a better understanding of drilling as a dynamic process, some researchers simulate drilling process by quasi static penetration of composite laminates by an indentor. Govekar et al. [7] studied the static penetration process in carbon-epoxy laminates subjected to blunt-ended punch. The typical force generated during the penetration process is shown in Fig. 1a. The force applied by the indentor increases until matrix crack-induced by delamination happens (Fig. 1a, point A), then a sudden drop occurs (point B). The stiffness of the plate is reduced, and as the load reaches its peak value (point C), a plug is formed. The force then drops rapidly (point D). After that, friction between the indentor and the hole provides the only resistance to the motion. Delamination is initiated by matrix cracks, located in the double-ply layers, and extends through the entire plate.

Rubio et al. [8] investigated the quasi-static impact perforation of Kevlar–polyester laminates by conical indentors. The load applied to the indentor during quasi-static tests vs. its displacement is shown in Fig. 1b. The load applied to the indentor increases due to both indentation and global deflection of the plate and reaches its maximum value (point A), then a plateau is reached related to fiber failure (point B). On complete penetration, the load rapidly drops to a much lower level as friction against the side of the hole provides the only resistance to the motion (point C). Goldsmith et al. [9] showed similar results for quasi-static penetration of woven graphite-epoxy laminates by conical indentors. Local deformation (bulging) and fiber failure constituted the major energy absorption mechanism.

Based on previous discussions, some researchers used static force to analyze the delamination mechanism during the drilling process [10–11]. Hocheng et al. [12] determined the critical thrust force leading to onset of delamination based on the classic plate bending theory and linear elastic fracture mechanics (LEFM). To drive Eq. (4), they assumed the force is concentrated and quasi-static applied along the drill axis.

$$F_{cr} = \pi\sqrt{32G_{IC}D} \quad (4)$$

where G_{IC} and D are critical energy release rate in mode I and bending stiffness of the composite, respectively. They used similar approach to find critical thrust force for different drill bits (saw drill, candle stick drill, core-center drill, core-saw drill and step drill) considering the effect of pilot hole and back-up plate [13].

1.3. Damage assessment

The damage during drilling of glass/epoxy laminates affects the mechanical properties of the part. The problem is complicated by the fact that internal damages cannot be detected by visual inspection. With the purpose of evaluating the effect of any damage on a component, determining the behavior of damage during the loading of the component is recommended. Current non-destructive damage assessment techniques include offline and online methods; however, offline methods cannot be used to assess damage under loading. Hence, the damage occurring due to drilling GFRPs requires the use of on-line monitoring techniques. The main goal of on-line monitoring of composite drilling is generating damage-free holes. The drilling process could be monitored by studying the corresponding response of the material. Among numerous on-line monitoring techniques, Acoustic Emission (AE) is considered to be one of the most accurate monitoring methods in the machining field [14–18].

Acoustic emission is defined as the generation of transient elastic waves by the rapid release of energy from localized sources within a material undergoing deformation. When a component is

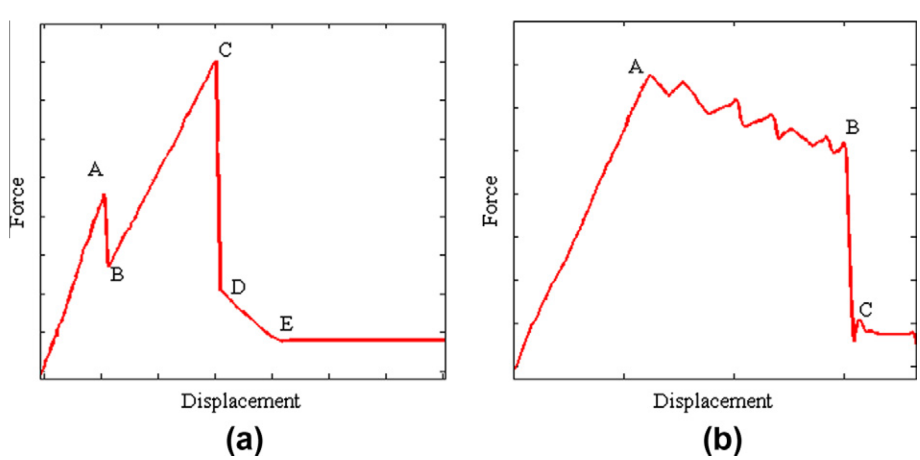

Fig. 1. Load versus displacement in static test (a) flat cylindrical indentor [21] (b) conical indentor [22].