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Review Article

A Review of Drilling of Carbon Fiber Reinforced Plastic Composite Materials

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Abstract

The use of composite laminates (CFRP, GFRP, and fiber metal composite laminates) is attractive for many applications (such as aerospace and aircraft structural components) due to their superior properties and, as a consequence, the number of papers focused on relevant aspects concerning the machinability of such materials has also increased. Composite laminates are regarded as hard-to-machine materials, which results in low drilling efficiency and undesirable drilling-induced delamination. . This review paper summarizes an up-to-date progress in mechanical drilling of composite laminates reported in the literature. The principal aim of this work is to present a literature survey on the drilling of composite materials, more specifically on drilling of carbon fiber reinforced plastics. Aspects such as tool materials and geometry, machining parameters and their influence on the thrust force and torque are investigated. Additionally, the quality of the holes produced is also assessed, with special attention paid to the delamination damage. . It is intended to help readers to obtain a comprehensive view on mechanical drilling of composite laminates.

Keywords: *CFRP, GFRP, Composite laminates, Drilling-induced delamination, Delamination damage, Machining parameters.*

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1. Introduction

Composite materials are increasingly used in various fields of science and engineering because of their unique and desirable properties. As a result of these properties and potential applications, there is a strong need to understand the issues associated with fabricating and machining of composite materials better. In the past few decades, the use of composites has increased dramatically, continually leading to new applications. The use of composite laminates (CFRP, GFRP, and fiber metal composite laminates) is attractive for many applications (such as aerospace and aircraft structural components) due to their superior properties.

Carbon fiber reinforced plastic (CFRP) composite materials has unique mechanical and functional properties due to the combination of its constituent materials that possesses desirable properties. The constituents are typically available in the form of carbon fiber reinforcement embedded in a plastic matrix. The high strength–to-weight ratio, wear resistance and corrosion resistance of CFRP materials make it suitable for various vital applications such as aerospace, automobiles, sporting goods, biomedical, post strengthening of beams, etc. In order to suit the different structures of such applications, machining of CFRP materials are carried out and drilling is one such inevitable operation to join different structures. The article presents a review on the effects of drilling parameters on the machinability parameters in drilling polymeric composite materials. Drilling parameters will include: feed, speed, drill geometry, drill wear, drilling with special tools, and composite materials parameters. The machinability parameters will include: thrust force, torque, surface roughness, delamination, residual strength, and mechanical and thermal damages of the composite materials. In addition, survey on the delamination measurement techniques and analytical damage models will be reported.

2. Drilling of Composites

Drilling of composite materials is different than drilling of metals as drill has to pass alternatively through plastic (matrix) and fiber (reinforcement) which have different properties. The difference in the physical and chemical properties of the constituents makes the understanding of the mechanism of material removal quite complex. Material removal during drilling of composites involves series of fractures aided by diverse nature and uneven load sharing between matrix and fiber (Bhattacharyya D *et al*, 1998).

2.1 Delamination Mechanisms

Damages associated with drilling FRP composites were observed, both at the entrance as well as at the exit of the drilled hole, in the form of peel-up and push-out delaminations, respectively (Khashaba UA *et al*, 2007).

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The drilling action results in damage of the composite material around the hole. It affects the surface finish of the drilled hole and also results in performance deterioration of the final composite product (Davim JP *et al,* 2009).This damage can be estimated and characterized (Davim JP *et al,* 2007; Hough CL *et al,* 1988).Delamination (failure of inter-lamina bond), fiber pull-out (failure of matrix–fiber bond), micro cracking (micro cracks on machined surface), matrix burning (burning of matrix due to machining) and chipping and spalling (small uncut fibers left in drilled composite) are some of the common damage forms (Durao LMP *et al,* 2006).The two mechanisms associated with delamination during drilling of polymer–matrix composites (PMCs) are known as peel-up at the drill entrance and push-down at the drill exit as shown in figure1.

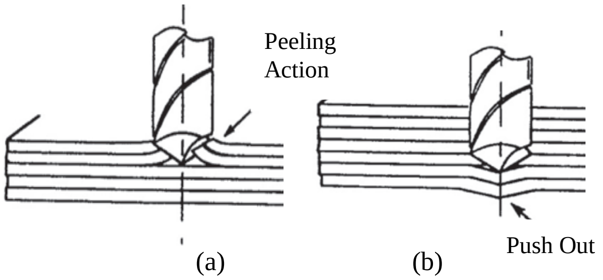

Figure1. Mechanisms of delamination: (a) peel-up at entrance and (b) push-out at exit (Khashaba UA *et al,* 2007).

Delamination in CFRP composite laminates were correlated by multiple linear regression technique relating cutting velocity and feed rate with the delamination. The confirmation tests showed that error associated with the delamination factor has excellent correlation (Davim, J. P. *et al,* 2003).At higher cutting speed, the tool wears out quickly resulting in increase in thrust force and torque (Lin SC *et al,* 1996).This results into larger entrance and exit burrs and larger damage rings (Ramulu M *et al,* 2001).Combination of higher speed with lower drill point angle is suitable for reducing delamination (Gaitonde VN *et al,* 2008).Drilling at higher speeds can afford increased feed rates and still prevent damage due to delamination (Rubio JC *et al,* 2008).

2.2 Thrust Force

The thrust force, in drilling polymeric composite materials, has been cited as the cause of delamination that increased by increasing the feed rate. Some investigators developed empirical relationships that correlated the drilling forces with feed and drill diameter. Equations (1) and (2) are typical example for the empirical relationships that used for prediction thrust force and torque, respectively, in drilling operations (Won MS *et al,* 2002; Dharan CKH *et al,* 2000).

$$F_Z = K_1 (f*d)^{1-a} + K_2 d^2 \qquad (1)$$

$$T = K_3 (f)^{1-a} d^{2-a} \qquad (2)$$

where F_Z is the thrust force in expressed in N, T the torque expressed in Nm, and K_i(i¼) the constants to be determined from the experimental data using the least squares method. The drill diameter, d, and feed, f, are expressed in mm and mm/rev, respectively. The values of constants in drilling woven carbon fiber reinforced epoxy (CFRE) composite are: a¼0.34, K_1¼40.77, K_2¼0.36, and K_3¼0.0066.10 If a pilot hole is pre-machined the thrust force can be calculated using equation (2) with K_1¼3.5 and K_2¼0 (Rao BS *et al,* 2008).

The size of the delamination zone is related to the thrust force developed during the drilling process (Ramulu M *et al,* 2001) and there is a ‘‘critical thrust force’’ below which no damage occurs (Hocheng H *et al,* 2005).Drilling a pilot hole prevents the contact of chisel edge of the drill with the composite plate thus reducing the thrust force that causes delamination (Tsao CC *et al,* 2003).Different geometry of the tool can also lower the delamination by lowering the thrust force [18]. It has been established that it is not only thrust force that influences the drilling induced damage, torque also plays significant role (Singh I *et al,* 2006).Torque is related to the feed rate and increases with increase in the feed rate (Ramulu M *et al,* 2001).Torque may shoot up towards the end of drilling due to chip jamming in the helix and this high torque may damage the tool (Oh YT *et al,* 2003).The authors worldwide have attempted optimization of the operating variables, tool materials, tool point geometry, theoretical modeling of the drilling forces and unconventional methods of hole making for minimization of drilling induced damage (Davim, J. P. *et al,* 2003; Gaitonde VN *et al,* 2008).

2.3 Surface Roughness

The different cutting parameters along the cutting edge of the drill tool accompanied with its helical path result in a complex surface roughness analysis. Dura˜o et al. (Dura˜o LMP *et al,* 2010).reported that the surface roughness results in drilling carbon fiber reinforced laminates were too scattered to allow for any valid conclusion (Khashaba UA *et al,* 2007) reported that surface roughness in drilling woven FRP composites was slightly increased with increasing the feed, while no clear effect of the cutting speed is observed.

Brinksmeier and Janssen (Brinksmeier, E *et al,* 2002) performed drilling of multi layer composite materials consisting of CFRP composite, Titanium and Aluminum alloys. Different carbide tools with improved geometries and coatings were investigated and compared with respect to cutting forces, tool wear, hole quality and chip formation. Also surface defects of the hole and the resulting diameter tolerances are affected due to high mechanical and thermal loads.

Damage free holes can be drilled in composites by using appropriate feed rate either manually or using automation. Automated drilling as against manual drilling is independent of skill of the operator and is suitable for mass production. Automated drilling essentially has: force and torque sensors, processor and controlled feed motor to accurately drill through the composite material. Processor based on the pre-fed logic manipulates sensor signal to calculate control voltage to be given to the feed motor. Processor logic can be developed on the basis of mathematical models of drilling and control theory. In the following sections, mathematical models and control theories used for automated drilling are discussed.

3. Modeling of Drilling Process

The key for reducing the delamination onset in drilling FRP composites lies in reducing the thrust force associated with drilling operation. It is believed that there is a 'critical thrust force' below which no damage occurs. If the critical thrust force is known, the machining efficiency can be increased and higher productivity can be achieved. The linear elastic fracture mechanics (LEFM) and classic plate bending theory were used by many investigators (Zhang LB *et al,* 2001) to predict the critical thrust force at delamination onset in drilling FRP composites.

Ho-Cheng and Dharan (Ho-Cheng H *et al,* 1990) (Figure 2) proposed model by which they show that at some point, the resulting stress exceeds the interlaminar bond strength causing an exit delamination zone as the tool pierces through the exit side.

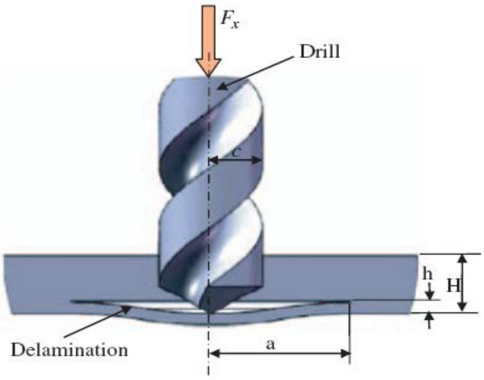

Figure 2 Circular plate model for delamination analysis

At this moment, the applied effort corresponds to the critical thrust force. It is noted that the global behavior of the laminate is considered as elastic and isotropic. The equation of energy balance, from LEFM, can be written as

$$G_I \pi (D+2a) da = F_Z dx - dU$$

where D is the drill diameter, F_Z the applied thrust force, x the displacement, H the thickness of the structure, h the uncut depth under the tool and the assumed size of an existing crack, G_I the energy release rate per unit area, and U the stored strain energy.

The analytical approach based on the Linear Elastic Fracture Mechanics (LEFM) method can be used to predict the onset of delamination in drilling of composite laminates. The empirical equation for the location of onset of delamination is:

$$h^* = 0.0000254 h_{ply} (h^*_{anisotropic}) (E_{22}/E_{11})^{0.62208} (G_{IC} E^*_C).$$

where h_{ply} is ply thickness of the composite laminate, $h_{anisotropic}$ is uncut depth corresponding to the critical thrust force, E_{22} is Young's modulus transverse to the fiber direction, E_{11} is Young's modulus parallel to the fiber direction, G_{IC} is critical crack propagation energy in mode-I and E^*_C is a complex material mechanical property constant (Tsao CC *et al,* 1997) .Thrust force and torque can be analytically modeled by considering the cutting force developed at the two major cutting edges of the drill as orthogonal machining. The model is based on simple shear or fracture across a single plane. The resulting thrust force and torque is:

$$F_t = c_1 F_c \tan(\beta-\alpha)$$

$$T = c_2 (F_c+\mu F_t) \rho R$$

Where:

$$Fc = [\Delta W \tau_s f \sin(k/2) \cos(\beta-\alpha)] / [2\sin\phi \cos(\phi+\beta+\alpha)]$$

is cutting force , $\Delta W = (\rho_i-\rho_{i-1})R/\sin k$ is elemental width, τ_s is in plane shear strength, f is feed per revolution, β is friction angle, α is rake angle, ϕ is shear plane angle, $\rho = r/R$, R is drill radius, r is radius.

Jung et al. (Jung JP *et al,* 2005) proposed a new formulation for the critical thrust force at delamination propagation in multidirectional laminates. The delamination zone was assumed to be elliptical and subjected to a concentrated load with clamped boundary conditions. The load causes bending and twisting to the mid-plane extension and shear of the plate. The starting relation is the energy balance equation

$$Pdw_0 = G_I da + dU$$

where G_I is the energy release rate per unit area, dU the infinitesimal strain energy, dA the increase in the area of the crack, P the thrust force, and dw_0 the infinitesimal deflection at the center of the laminate.

4. Assessment and Measurement of Delamination

Tagliaferri et al. (Tagliaferri V *et al,* 1990) used the diffusion phenomena of the liquid into the material through the cut surface to measure the damaged area around the hole with optical microscope at 10 magnification. It was noted that the actual value was strongly affected by the immersed time. Therefore, they carried out all the measurements after 24 h from the immersion of the specimens in the liquid. Different Visual inspection techniques for measuring the delamination size in drilling polymeric composites are widely used by many investigators. These techniques includes: tool marker's microscopes with different magnification, digitizer of CCD camera with the aid of image digitalization and processing, and Autocad method, Lee-Sullivan and Spedding (Lee-Sullivan P *et al,* 1997) used a surface roughness measuring instrument (Rank Hobson Surtronic 3P) as a non-destructive technique for detecting delamination onset during tensile testing of GFRE specimens notched with a circular hole. Khashaba3 used a similar approach to detect the existence of delamination in drilling GFRE composites with 8mm diameter at high feed (Abra´o *et al* 2008) reviewed the principal parameters used to evaluate delamination after drilling. These parameters divided into two categories: dimensional and non dimensional parameters. Dimensional parameters include: delamination area; difference between the radii of the maximum damage and drilled hole; average of two perpendicular measurements of the diameter of the damage area; and sum of lengths of the internal crack. The non-dimensional parameters allow comparisons among the results from distinct authors, which include: ratio of the drill radius to the delamination radius; ratio of the damage area to the hole area; and ratio of the maximum diameter of the delamination zone to the hole diameter.

Concluding remarks

The following concluding remarks were drawn from the extensive review on damage-free in drilling polymeric composite materials. These remarks are extremely important from the scientific and industrial point of view:

1. Both thrust force and torque are responsible for delamination during drilling of composites still there is no comprehensive mathematical model consisting of thrust force, torque and feed rate. All the classical models available have modeled thrust force or torque independently with feed rate.
2. Until now, no machining chart covers the various types of polymeric composite materials compared with metallic materials, but one might find some traces on machining some types of composites. So many research works are needed to develop machining charts that enables selecting the suitable cutting conditions for damage-free in drilling composite materials.
3. The variable feed rate strategy in which feed rate is decreased toward the exit of the hole has been addressed for drilling composites with delamination-free holes.
4. There is no work in literature wherein thrust force and torque are controlled simultaneously during drilling.

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