AN ANALYTICAL MODEL FOR PREDICTING CRITICAL FEED RATE IN DRILLING OF COMPOSITE LAMINATES

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Abstract

The thrust force during drilling is one of key indexes to describe machinability of composite laminates owing to the fact that it directly affects the quality of drilled holes, especially drilling-induced delamination. The size of drilling-induced delamination zone has been shown to be related to the thrust force during drilling composite laminate, and it is believed that there is a critical thrust force below which no delamination appears. However, thrust force strongly depends on drilling parameters and it is not possible to control it directly. Thrust force can be correlated with feed rate. This paper presents an analytical model for predicting critical feed rate at the onset of delamination propagation. The model proposed is based on linear elastic fracture mechanics, classical plate bending theory and the mechanics of oblique cutting.

1. Introduction

The importance of composite materials has been growing over the last decade. Their unique properties such as high strength and high stiffness made them more suitable for different industries. Nevertheless, some problematical issues remain concerning the use of composite laminates. The high cost of materials and complexities in their manufacturing are the most serious problems. Specimens fabricated from composites are endeavored to be made net shape. However, the existing manufacturing technique of fabricating to near-net shape is incomplete unless the component is subjected to secondary machining operations based on the requirement [1, 2].

Amongst various machining operations for composite laminates, conventional drilling is perhaps the most frequently used machining operation in industries due to the need for assembly of components in mechanical structures. Drilling composites differ vastly from drilling conventional materials due to the anisotropic and non-homogeneous characteristics of these materials. Exclusive problems associated with drilling composites such as fiber pullout, matrix cracking and delamination are generally referred to whenever the limitations of these materials are listed [3].

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One of the most common problems is related to the need of free-delamination drilling. Delamination reduces the strength and stiffness and hence limits the life of a structure. In general, delamination happens both at the entrance and the exit planes of the laminate as shown in Fig. 1 [4]. There is a peeling effect phenomenon on the periphery of the cutting edges of the drill which causes peel-up delamination at the drilled hole entry. Push-down delamination at the hole exit appears when the thickness of the uncut material located under the toll decreases and therefore the bending stiffness of the uncut material decreases. In this circumstance, the thrust force exerted by the tool eventually exceeds the inter-ply bonding strength and results in delamination. It is reported that there is a critical value for thrust force below which delamination is negligible [5]. Analytical study of this thrust force is thus interesting in order to reduce delamination.

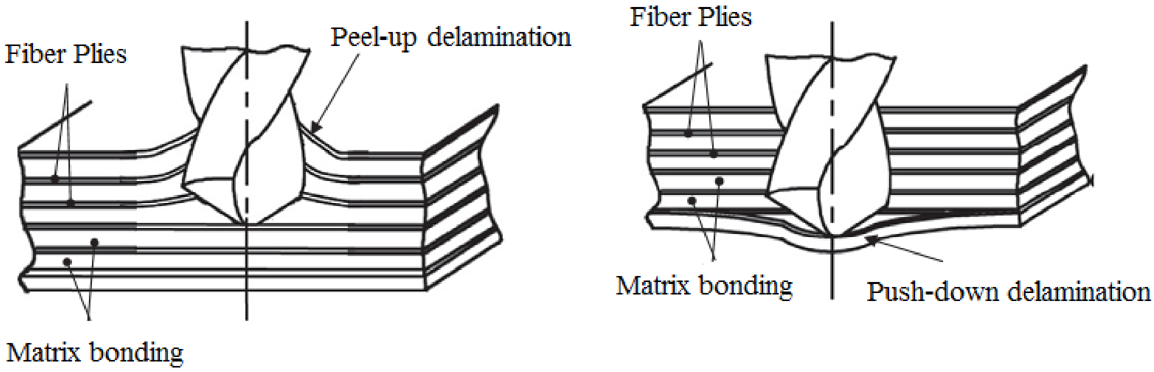

Figure 1. Different delamination mechanisms in drilling composites.

Several researchers attempted to model critical thrust force for delamination propagation. The first analytical model was proposed by Hocheng and Dharan [6]. They employed linear elastic fracture mechanics (LEFM) and classical plate bending theory to formulate an analytical model to predict the critical thrust force (the minimum force above which delamination is initiated) at the onset of delamination. The isotropic behavior and pure bending of laminate are assumed in their model. Jain and Yang [7, 8] developed this model, considering the anisotropy of the material and hypothesizing that the cracks are elliptical. In their model, the drilling thrust force is simplified by a representative single concentrated central load. Hocheng and Tsao [9] extended this model, taking into consideration a series of loading types for various drill types.

Thrust force depends on drilling parameters and it is not possible to control it directly. Relating thrust force with feed rate is important because feed rate can be directly controlled. Analytically, several cutting force models for drilling composite materials are developed based on orthogonal and oblique cutting [10-12]. One of the most accurate published cutting force prediction models for drilling composite is presented by Langella et al. [12]. They used the orthogonal cutting model suggested by Caprino et al. [13] as a basis by observing that during a drilling process the prerequisites for orthogonal cutting are met for an infinitesimal instant.

The critical thrust force in the model developed by Hocheng and Dharan, the isotropic behavior for laminate is assumed, which is not the case for anisotropic composite materials. In this paper, we aim to extend this theory, considering the anisotropy of the material to find the critical thrust force and also feed rate at the onset of delamination. For this aim, we use the oblique cutting model proposed by Langella to describe the correlation between thrust force and feed rate.

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2. Oblique cutting model

For traditional drilling process a fairly unified physical analysis can be carried out using basic orthogonal and oblique cutting models. The difference between these two models is the inclination angle which is zero in the case of orthogonal cutting. The presence of inclination angle between the cutting edge and the normal to the tool motion direction generates a third force component (lateral force component) when compared with the planar situation of the cutting forces in orthogonal cutting. This effect makes the mathematical derivations more complicated. Hence, in many cases orthogonal cutting is assumed for simplifications reasons. Caprino et al. [13, 14] conducted a series of experiments on orthogonal cutting of fiberglass composites to find an analytical model for cutting forces as shown below:

$$F_{hu} = 4.29 + 257.804 \times 10^{-0.019\gamma} t \quad (1)$$

$$F_{vu} = 95.3 \times 10^{-0.02\gamma} t^{0.5} \quad (2)$$

where F_{hu} and F_{vu} are, respectively, the horizontal and vertical forces per unit of width of the tool, γ is the rake angle and t is the cutting depth.

This model is only valid for orthogonal cutting which limits its application for the drilling process which is three dimensional and oblique. Cutting speed, inclination angle, relief angle and rake angle change depending on the radius along the cutting lip of the drill. Langella et al. [12] extended the scope of these relations for oblique cutting as given below:

$$T_L = 2B \times 10^{-1.089\gamma_m} (\frac{f}{2})^{0.5} G \quad (3)$$

$$T_C = 2C \times 10^{-1.089\gamma_c} (f)^{0.5} t_c \quad (4)$$

where T_L and T_C are, respectively, the resultant thrust force applied on cutting lips and chisel edge regions, f is the feed rate, t_c is the half the thickness of the chisel edge, γ_m is the average rake angle and γ_c is the chisel edge rake angle. The values of unknown parameters, B and C, and geometrical parameter G are determined as explained in [12].

The total thrust force will be the sum of the part values generated by cutting lips and the chisel edge.

3. Delamination Propagation Model

3.1. Physical Model

In drilling composite laminates, when the drill bit approaches the exit side, the uncut plies withstanding the thrust force become more susceptive to deformation owing to decrease of its thickness. Eventually, the thrust force applied to the uncut plies exceeds the interlaminate bond strength and delamination occurs. This happens before the laminate is completely penetrated by the drill.

The energy balance equation at the onset of delamination propagation gives:

$$dU_d = dU - dW \quad (5)$$

where dU is the infinitesimal stored strain energy, dW is the infinitesimal work done by the thrust force F_{th} and deflection of plate dw, and dU_d is the infinitesimal strain energy absorbed by crack growth which is as follows:

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$$dU_d = G_{IC}.dA \tag{6}$$

where dA is the increase in the area of delamination crack and G_{IC} is the critical strain energy release rate in mode I, which is assumed to be constant according to Saghizadeh and Dharan [15].

To calculate the work done W and stored strain energy U, the deflection of plate needs to be determined. According to the classical plate bending theory, the transverse displacement w of a thin plate subjected to uniformly distributed load q over a central circular area is expressed as [16]:

$$\nabla^2 D \nabla^2 w = q \tag{7}$$

where D is the bending rigidity of the plate. If the bending rigidity D is constant throughout the plate, the plate equation can be simplified to:

$$\nabla^4 w = \frac{q}{D} \tag{8}$$

replacing the bending rigidity with equivalent bending stiffness for an orthotropic plate yields:

$$\nabla^4 w = \frac{1}{rdr} d\left(r\frac{d}{dr}\left[\frac{1}{r}\frac{d}{dr}\left(r\frac{dw}{dr}\right)\right]\right) = \frac{q}{D'} \tag{9}$$

where equivalent bending stiffness for an orthotropic plate is:

$$D' = \frac{3D_{11} + 2D_{12} + 4D_{66} + 3D_{22}}{8} \tag{10}$$

3.2. Physical Model

Fig. 2 depicts the schematic of delamination in the last uncut laminae of the work-piece. In this figure, T is the total thrust force exerted by a twist drill at the center of plate, R is the drill radius and a is the radius of crack.

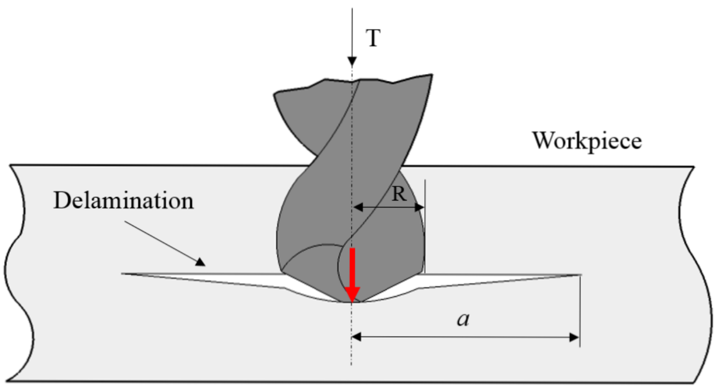

Figure 2. Delamination propagation model.

According to the Eq. (9), for a circular plate with clamped edges subjected to a concentrated central force, the deflection is given by:

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$$w(r) = \frac{T}{16\pi D'}\left(2r^2 \ln\frac{r}{a} + (a^2 - r^2)\right) \tag{11}$$

where the total thrust force T is the sum of force applied on the cutting lips and chisel edge expressed as below in the form of exponential:

$$T = T_L + T_C = \frac{K_L}{e^{\alpha_L \gamma_m}}\sqrt{f} + \frac{K_C}{e^{\alpha_C \gamma_C}}\sqrt{f} \tag{12}$$

The stored strain energy, the work done and the strain energy absorbed by crack growth are expressed as the following equations, respectively.

$$U = \frac{T^2 a^2}{32\pi D'} \tag{13}$$

$$W = \frac{T^2 a^2}{16\pi D'} \tag{14}$$

$$U_d = G_{IC}.A \tag{15}$$

and the energy balance equation gives:

$$G_{IC} 2\pi a = \frac{T^2}{16\pi D'} - \frac{T^2 a}{8\pi D'} \tag{16}$$

finally the critical thrust force and feed rate at the onset of crack propagation can be calculated as below:

$$T_{critical} = \pi\sqrt{32 G_{IC} D'} \tag{17}$$

$$F_{critical} = \frac{32\pi^2 G_{IC} D'}{\chi^2} \tag{18}$$

where the constant χ is calculated as below:

$$\chi = \frac{K_L}{e^{\alpha_L \gamma_m}} + \frac{K_C}{e^{\alpha_C \gamma_C}} \tag{19}$$

To avoid drilling-induced delamination, the applied thrust force and adjusted feed rate should not exceed these critical values.

4. Discussions and Conclusions

In this paper, analytical models to predict critical thrust force and feed rate at the onset of delamination are proposed. To achieve this aim, the oblique cutting model proposed by Langella was employed to determine an analytical relation between feed rate and thrust force. The force exerted by the rotating twist drill bit to the laminate is assumed to be a single concentrated force at the center which is the sum of the part values generated by cutting lips and the chisel edge. Then, elastic fracture mechanics and classical plate bending theory were used to determine the critical thrust force above which delamination is initiated. Finally, the critical feed rate for the onset of delamination was modeled by combining the resulting equations for oblique cutting model and critical thrust force. The results of the proposed analytical models can be investigated from different viewpoints. For example, the effects of each drill

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geometrical parameters, such as point angle, helix angle or rake angle, on critical feed rate can be studied. However, it is not possible to discuss all these findings and investigations in this article. This model provides the possibility of using optimal feed rate directly to avoid delamination. Detailed results of the proposed models including experimental data will be published in future articles.

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