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Critical thrust and feed prediction models in drilling of composite laminates

Navid Zarif Karimi [a,*], Hossein Heidary [b], Giangiacomo Minak [a]

[a] Alma Mater Studiorum, Università di Bologna, Department of Industrial Engineering DIN, Viale del Risorgimento 2, 40136 Bologna, Italy
[b] University of Tafresh, Department of Mechanical Engineering, First of Tehran Road, 7961139518 Tafresh, Iran

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ABSTRACT

Drilling induced delamination has been recognized as a major problem during drilling of composite materials. The size of the delamination zone has been shown to be related to the thrust force. 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, the most important parameter affecting thrust force. This paper presents analytical models to predict critical thrust force and feed rate at the onset of delamination. The model proposed is based on elastic fracture mechanics, classical plate bending theory and the mechanics of oblique cutting. An advantage of this model over other proposed models is that to avoid delamination via thrust monitoring, the thrust force will need to be sensed and used in adaptive control, while optimal feed rate can be used directly in CNC command generation to maximize productivity.

1. Introduction

Among various drilling processes for fiber reinforced composite laminates, conventional drilling with twist or special drill bits has remained the most frequently and economically used machining operation in industry. Drilling of FRPs is a complex process and it differs significantly in many aspects from machining of conventional metals and alloys due to the anisotropic and non-homogeneous characteristics of these materials. During the drilling of composite materials many problems arise which do not occur in other materials. Among various defects caused by drilling, delamination is known as the most prevalent life limiting damage growth mode [1–4].

Delamination is an inter-ply failure phenomenon, which is a highly undesirable problem and occurs due to localized bending in the zone sited at the point of drill contact. At the beginning of the drilling process, the thickness of the composite laminate is able to withstand the cutting force. As the drill bit approaches the hole's exit side, the cutting force applied to the uncut laminae of the workpiece exceeds the inter-ply bonding strength and results in delamination [5–8].

It has also been observed that drilling-induced delamination is directly related to the component of cutting force along the drill axis known as thrust force, and it is reported that there is a critical value for thrust force below which delamination is negligible [9]. Analytical study of this thrust force is thus interesting in order to reduce delamination.

Several researchers attempted to model critical thrust force for delamination propagation. The first analytical model was proposed by Hocheng and Dharan [10]. They employed linear elastic fracture mechanics (LEFM), classical plate bending theory and energy conservation theory to formulate an analytical model to predict the critical thrust force at the onset of delamination during drilling of composite materials. This model predicts a critical thrust force (the minimum force above which delamination is initiated) as a function of composite properties and drilled hole depth. The isotropic behavior and pure bending of laminate are assumed in their model. Jain and Yang [11,12] developed this model, considering the anisotropy of the material and hypothesizing that the cracks are elliptical. They also observed that the chisel edge has a greater contribution to the thrust force than cutting lips. In their model, the drilling thrust force is simplified by a representative single concentrated central load. Hocheng and Tsao [9,13–15] extended this model, taking into consideration a series of loading types such as circular load, concentrated centered load associated with circular load, distributed circular load and stepwise distributed circular load for various drill types such as saw drill, candle stick drill, core drill and step drill, respectively. In this analysis, the critical thrust force at the onset of delamination is predicted and compared with the twist drill.

* Corresponding author.
E-mail addresses: navid.zarif@unibo.it (N. Zarif Karimi), heidary@tafreshu.ac.ir (H. Heidary), giangiacomo.minak@unibo.it (G. Minak).

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Nomenclature

ε	drill point angle	F_{hu}	horizontal force
i	inclination angle	F_{vu}	vertical force
ψ	helix angle	T	total thrust force
φ	chisel edge angle	T_L	thrust force on cutting lips
γ	rake angle	T_C	thrust force on chisel edge
γ_s	static portion of rake angle	T_{exp}	experimental thrust force
γ_d	dynamic portion of rake angle	q	distributed load
γ_m	average rake angle	q_L	distributed load on cutting lips
γ_c	chisel edge rake angle	q_C	distributed load on chisel edge
r_c	chisel edge radius	a	crack radius
R	drill radius	w	deflection of plate
ρ	normalized radius	A	delamination area
t_c	half the thickness of the chisel edge	D	flexural rigidity
t	cutting depth	D'	equivalent flexural rigidity
f	feed rate	U_d	strain energy absorbed by crack growth
G	geometrical parameter	U	stored strain energy
K_n	specific energy for vertical force	W	work done
$K_{n,chisel}$	specific energy at chisel edge	G_{IC}	critical strain energy release rate in mode I
F_h	projection of force on drill axis		

Thrust force strongly depends on drilling parameters and it is not possible to control it directly. Relating thrust force with feed rate, the most important parameter affecting thrust force, is important because feed rate can be directly controlled. A series of empirical models were developed to correlate the drilling thrust force and feed rate by using linear regression analysis for various types of composite materials [16–21]. These models are only applicable for specific drilling conditions and a type of material. Analytically, several cutting force models for drilling composite materials are developed based on orthogonal and oblique cutting [22–24]. One of the most accurate published cutting force prediction models for drilling composite is presented by Langella et al. [24]. They used the orthogonal cutting model suggested by Caprino et al. [25] as a basis by observing that during a drilling process the prerequisites for orthogonal cutting are met for an infinitesimal instant. Only two semi-empirical coefficients are evaluated in this model and calibrated by means of simple linear regression. The model satisfactorily matches the corresponding experimental findings, specifically for drills with a constant point angle rather than the drills with changing point angles. They also provided a detailed analysis of the difficulties associated with the action of the chisel edge during drilling.

The critical thrust force in the model developed by Hocheng and Dharan for twist drill bits simplified the drilling thrust force by a representative single concentrated central load. However, the whole thrust force in the drilling process is rather spread over the cutting lips and chisel edge. Moreover, the isotropic behavior for laminate is assumed in their model, which is not the case for anisotropic composite materials. In this paper, we aim to extend this theory, considering the anisotropy of the material and a series of loading models to find the critical feed rate at the onset of delamination. For this purpose, we use the oblique cutting model proposed by Langella to describe the correlation between thrust force and feed rate.

2. Simplifying assumptions

1. The effect of drill rotation is neglected. Most researchers indicated that the torque generated during the drilling process has less effect on delamination than thrust force [26,27]. Mode III delamination caused by tool rotation needs a higher level of energy to be activated. Hence, mode III is regarded as having secondary significance in the analysis of drilling-induced delamination.
2. The composite plate is assumed to be circular and single layer orthotropic.
3. The composite plate is assumed to be clamped at the edges.
4. The applied forces over the cutting lips and chisel edge are assumed to be distributed uniformly in their corresponding regions.

3. Oblique cutting model

Caprino et al. [25,28]conducted a series of experiments on orthogonal cutting of fiberglass composites to find an analytical model for cutting forces as shown below:

$$F_{hu} = 4.29 + 257.804 \times 10^{-0.019\gamma} t \ \text{[N/mm]} \tag{1a}$$

$$F_{vu} = 95.3 \times 10^{-0.02\gamma} t^{0.5} \ \text{[N/mm]} \tag{1b}$$

where F_{hu} and F_{vu} are, respectively, the horizontal and vertical forces per unit of the width of the tool, γ is the rake angle and t is the cutting depth as shown in Fig. 1.

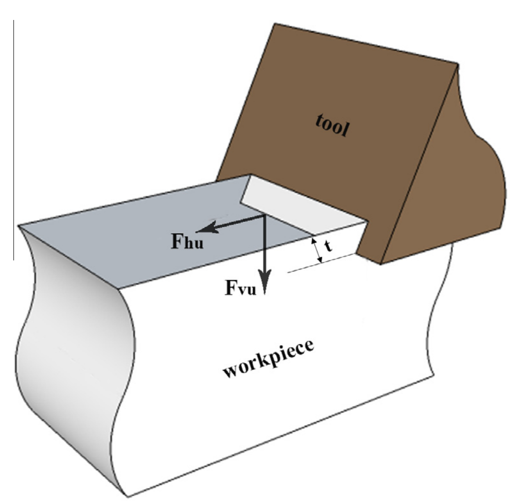

Fig. 1. Cutting forces in orthogonal model.