ISSN: 2458 – 7397

Journal of Advances in Science and Technology Research (JASTER), Volume 1, Number 1, March 2015, pp1-3

An Empirical Scheme for Drilling Delamination-free Holes in Composites

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Abstract

Composite materials have many attractive features. Despite this, several problems can arise during secondary processing such as delaminations during drilling. In this article a drilling envelope is developed to establish a zone for process parameters within which delamination-free operations may be performed. A 3-axis machining center along with tooling that includes solid carbide twist drills, a heavy duty clamping vise and a laser extensometer are deployed for measuring the tests. The material employed in is a 28-ply carbon fiber/epoxy composite laminate of 8.8 mm thickness, containing unidirectional carbon fibers of type T-700. A series of drilling experiments are performed to generate values of the bulge height at tool exit and the corresponding crack size at the piercing point for different feed rates and cutting speeds. A specified maximum crack size less than the hole radius leads to a delamination-free operation. This may be achieved by selecting the feed and cutting speed from the delamination-free zone of the drilling envelope. The results show promising prospects of the potential of the approach to reduce delamination damage in drilling.

Keywords: Composites, drilling, empirical, delamination envelope

Introduction

Machining-induced delaminations are a very serious defect during drilling of fiber-reinforced composites laminates. Schemes for modeling delamination include those based on: linear elastic fracture mechanics (Zhenchao, Kaifu, Yuan, Shunuan, & Hui, 2014), growth under fatigue loading (Yibing, Runze, Tishun, & Yongming, 2014), the influence of machining parameters (Bosco, Palanikumar, Durga, & Velayudham. 2013), among others. Empirical methods for studying delamination are few. Those found in the literature include Tsao, & Hocheng (2003), and Davim & Reis (2003). The latter employed a combination of Taguchi techniques and Analysis of Variance to study the problem. Their objective was to establish a correlation between cutting velocity and feed rate, and between cutting velocity and delamination. They claimed to obtain this correlation by multiple linear regression. However, it is not known whether these results have been independently verified. It is clear that the factors that influence delaminations are numerous and so far no one has considered many of them in any satisfactory fashion. From above it can be seen researchers generally have handled the problem in a piecemeal manner, an approach that does not guarantee optimal solution. Proceeding beyond the above references, it is noted that only very few researchers have considered material hardness as a factor. Ho-Cheng and Isao (2003), Won and Dharan, (2002), all examined the effects of different drill geometries on delamination damage while Shukla and Khanna (1993) studied the nature of fiber closing forces on the advancing delamination crack. Saghizadeh and Dharan (1986), further examined the relationship between fracture toughness and considered loading rate effects. Dharan and Saghizadeh formulated a model that estimates the relative contributions of the matrix and the fiber matrix interface to overall delamination fracture toughness.

The objective of the present work is to expand on the work of Sackey & Owusu-Ofori (2004), who suggested using an empirically determined index to characterize the delamination behaviour of fiber-reinforced composite laminates (FRCLs) in drilling. The aim of this work is develop a material characterisation drilling envelope for parameter selection in the drilling of fiber-reinforced composite laminates. Delamination-free operation may be achieved by selecting the cutting parameters from the delamination-free zone of the envelope.

Experimental Procedure and Results

The set-up comprises a Supermax YCM vertical (3-axis) machining center with FANUC Series 18-MC controller. Tooling include solid carbide twist drills, a heavy duty clamping vise and a laser extensometer for measuring the bulge. Material employed in the study is a 28-ply carbon fiber/epoxy composite laminate of 8.8 mm thickness, containing unidirectional carbon fibers of type T-700. A series

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of drilling experiments are performed to generate values of the bulge height *(Hb)* and the corresponding crack size *(ap)* at the piercing point for different feed rates and cutting speeds. This enables calculation of the drilling delamination index *S*, from which values of *e* are determined from Equation 1, (Sackey and Owusu-Ofori, 2004).

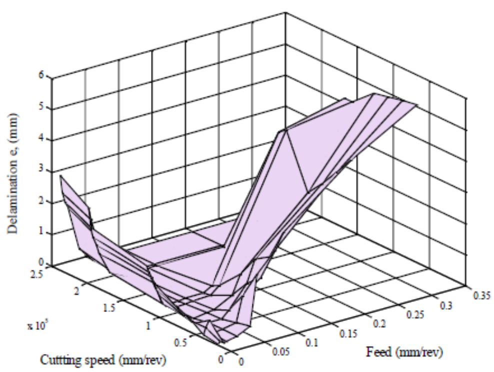
$$e = \left(a_p + \frac{S}{2}\left(\frac{d}{2\tan\theta} - H_b \right) \right) - d/2$$

where *S* = drilling delamination index,
θ = one-half drill point angle,
Hb = bulge height, *d* = tool diameter.

Each set of values comprising *f*, *Vc*, and *e*, is then plotted to generate the delamination envelope.

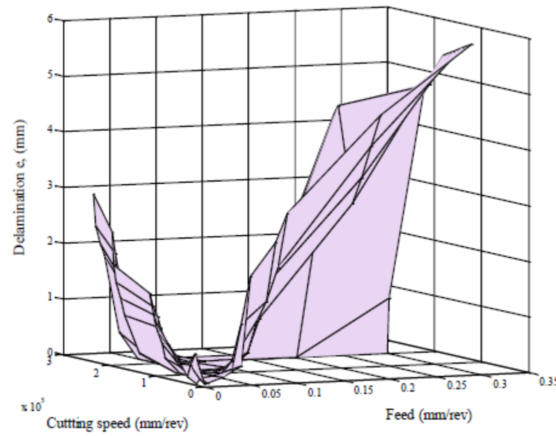
Results, Observations and Discussion

The results are presented in Figures 1 and 2 respectively for quarter-inch and half-inch tools respectively. The horizontal plane represents the feed (*f*) versus the cutting speed (*Vc*) while the vertical axis is the net delamination amount, *e*. Both figures reveal a narrow window within the envelope in the horizontal plane that could be used as a basis for delamination-free operation.



(a)

Figure 1: Delamination envelope for 28-ply laminate with quarter-inch tool



(b)

Figure 1. Delamination envelope for 28-ply laminate with quarter-inch tool: (a) view 1 (b) view 2

In the case of Figure 2a, i.e. the ½ inch drill, the front portion of the window is set back, indicating that results do not exist for relatively low values of the cutting parameters. Figure 2b clarifies this feature further. Nevertheless, it is clear that the general shapes of the two diagrams are similar. The starkest differences are observed near the low-feed, low-cutting speed zones of the two graphs.

In addition control equations may be extracted from the process windows. Each model provides paired values of the cutting speed and feed that would produce delamination-free holes for the indicated tool diameter. An average line may be used as an estimate for the delamination-free zone. It is found that for the half-inch tool ($0.1 \leq f \leq 0.3$ mm/rev):

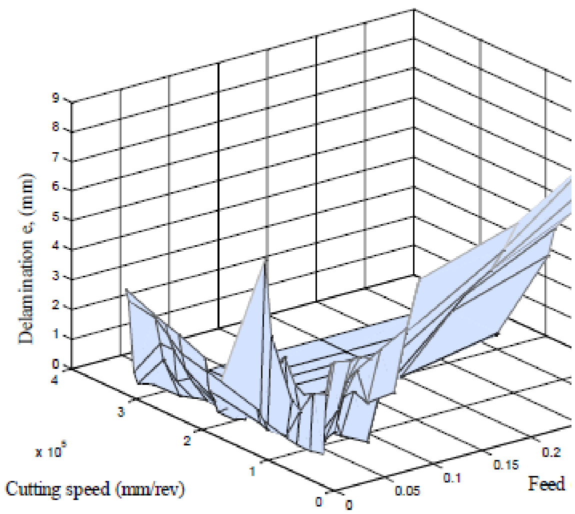
$$Vc = 300{,}000f + 230{,}000 \text{ mm/min} \quad (1)$$

and for the quarter-inch tool ($0.03 \leq f \leq 0.1$ mm/rev):

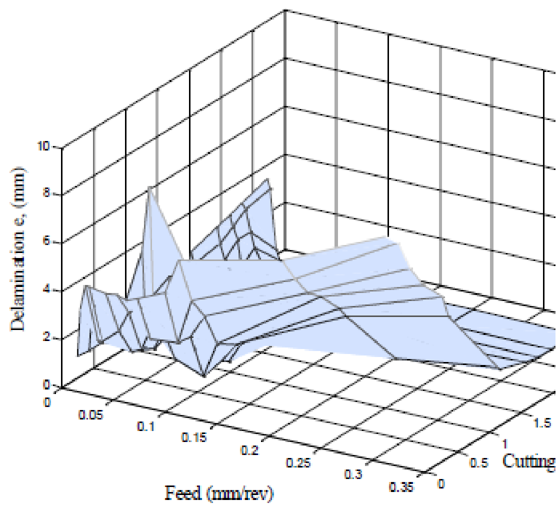
$$Vc = 2{,}400000f \text{ mm/min} \quad (2)$$

Concluding Remarks

A delamination envelope has been developed that may be used for the estimation of delamination crack size for given values of feed and cutting speed. A control equation extracted from the solution zone for a given tool diameter yields paired values of the feed and cutting speed that may yield optimum operation. Thus, it is possible to achieve a delamination free drilling of composite laminate using conventional drills by drilling at optimum feeds and speeds extracted from the solution (delamination-free) zone of the delamination envelope.



(a)



(b)

Figure 2. Delamination envelope for 28-ply laminate with half-inch tool: (a) view 1 (b) view 2

In the machining of composites, a sound, consistent empirical methodology is needed to ensure that quality is always achieved. The conventional metal machining theories break down when an attempt is made to model delamination damage on these theories. The very different nature of composites must always be considered in formulating schemes for delamination-free operation, be they empirical or analytical.

Acknowledgment

Acknowledgement is to the Center for Aerospace Research (CAR) of North Carolina A&T State University for supporting this work.

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