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Modeling and tool wear in drilling of CFRP

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ABSTRACT

This paper presents the prediction and evaluation of thrust force in drilling of carbon composite material. In order to extend tool life and improve quality of hole drilling, a better understanding of uncoated and coated tool behaviors is required. This paper describes the development of a phenomenological model between the thrust force, the drilling parameters and the tool wear. The experimental results indicate that the feed rate, the cutting speed and the tool wear are the most significant factors affecting the thrust force. The model can then be used for tool-wear monitoring. The model presented here is verified by experimental tests.

1. Introduction

Carbon fiber-reinforced polymer composites materials (CFRP) are characterized by a combination of high properties (specific strength and stiffness, light weight, etc.), which make their use especially attractive for aircraft and aerospace applications [1]. However, these materials are extremely abrasive during the machining operations. Machining of CFRP is difficult due to their material discontinuity, inhomogenity and anisotropic nature. Thus, the choice of the cutting tool and the optimal cutting parameters is very important when cutting this kind of materials. The machining process affects significantly these materials leading to various modes of damages. This damage consists of various fiber breakage, matrix cracking, fiber–matrix debonding and plies delamination. To improve the quality of the machined surface, some problems such as surface delamination and fiber/resin pull-out have to be overcome. To achieve the desired surface quality, it is necessary to understand the physical mechanisms of the material removal and the kinetics of the machining process affecting the performance of the cutting tools. Compared to the machining of metals, studies on machining of composites are few and limited in number.

Koplev [2,3] was the first in 1980 to conduct a series of experiments under orthogonal cutting of carbon fiber-reinforced polymer composites (CFRP). The author concluded that the chip formation is strongly influenced by the fiber orientation and occurs through a series of successive ruptures. The surface quality and the delamination factor are strongly dependent on the cutting parameters such as the tool geometry and cutting forces. Crack propagation ahead of the tool tip (Mode I) was observed during machining of laminates with 0° fiber orientation and compression-induced rupture was noticed during machining of laminates with 90° fiber orientation. The cutting of negative fiber orientation graphite/epoxy composites was attributed to compression-induced shear failure by Arola et al. [4]. For the same range of fiber orientations Bhatnagar et al. [5] ascribed fiber breakage due to axial tension as the cutting mechanism. Pwu and Hocheng[6] suggested that the fibers break when the bending stresses exceeded the ultimate material strength. Arola and Ramulu [7] described the chip formation mechanisms during machining with a diamond-tipped tool. The authors explained that the chip formation is due to a brittle fracture independent of the fiber orientation. Arola and Ramulu observed from experiments that both cutting and thrust force registered a minimum in the 15–30° fiber orientation range and increased up to 90°.

Among the several machining processes, drilling is one of the most frequently used for the production of holes for screws, rivets and bolts. Delamination and surface finish in drilling composite materials have been found to be influenced by a number of factors such as feed rate, cutting speed, drill geometry, tool wear and tool

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material. Delamination remains the most serious damage mode as it reduces severely the load carrying capacity of laminated composite structures and, therefore, must be avoided (Abrate [8], Persson et al. [9,10]). The importance of tool geometry in delamination reduction is evidenced by several authors. Piquet et al. [11] suggested the use of a great number of cutting edges, in order to increase the contact length between tool and part, a point angle of 118° and a small rake angle.

In addition to experimental methods, an analytical way is also possible to predict the thrust force and delamination. Studies based on linear elastic fracture mechanics theory have proposed values for the critical cutting forces at the onset of delamination during composite drilling. If the thrust force is exceeded, delamination will occur. It is the uncut thickness that has to withstand the indentation force induced by the drill. This thickness tends towards zero as the drilling progresses, causing the critical thrust force to be lower when the drill bit approaches the exit side of the laminate. The first model was presented by Hocheng and Dharan [12]. The authors studied the onset of delamination in two different situations: push-out at exit and peel-up at entrance. Based on the energy balance equation, the expression for critical thrust force was modeled. Piquet et al. [11] considered the existence of a normal stress perpendicular to the ply surface. To obtain the final result, the part of the plate located beneath the drill has been modeled in terms of a thin circular orthotropic plate. This representation does not take into account the global deflection of the plate. It is only valid for a small number of plies under the drill. Zhang et al. [13] considered a different approach. In their model, the shape of the delamination is elliptical even when multidirectional composites are drilled. The ellipse has two principal directions aligned with the fiber direction and the transverse direction of the uncut ply below the drill tip. Jain and Yang [14] developed a model starting from Hocheng and Dharan [12], considering an elliptical shape of the delamination area.

Tsao and Hocheng [15] analyzed the effect of a backup plate on delamination. Results show that the use of a backup plate causes an increase in the critical thrust force, allowing for higher feed rates. In another work [16], Tsao and Hocheng conducted several experiences to prove the benefit of using special drill when compared to commercially available tools, like twist drill. In this study, it was possible to conclude that thrust force varies with drill geometry and with feed rate. More recently, Tsao and Hocheng [17] have presented the advantages of a core drill. The influence of spindle speed was relatively insignificant. Fernandes and Cook [18] investigated the thrust force during drilling with "one shot" drill bit. Their objective was to extend tool life and improve hole quality. For that, a mathematical model leading to the calculation of feed in order to keep thrust force under a critical threshold was developed. Finally, Tsao [19,20] evaluated the importance of pilot hole on delamination reduction when using core and saw drills. Pilot hole eliminates the chisel edge effect, reducing delamination hazard. The ratio of pre-drilled hole to drill diameter must be controlled in order to drill with higher feed rate without delamination. Recently, statistical tools had been used in the search for optimal cutting conditions or tool design. Tsao [21] applied the Taguchi method and analysis of variance.

The wear is often defined as the amount of matter lost by the tool. When wear is characterized by the appearance of ribbed bands formed by abrasion on the clearance face, the life criteria can be established from direct observations on the tool. The friction of the workpiece against the clearance face shows a frontal area of wear, whose height VB is more or less regularly. One can quantify the lifetime of tools by simply measuring the average width of wear VB. It is also possible to assess the damage of a cutting tool from indirect criteria based on performance or quality of machining. Thus, the surface condition and geometrical tolerances of the parts can be used as indicators of the level of wear. In drilling, for example, we can define the life of a drill by the number of holes drilled meeting certain quality criteria. From the wear criteria are established the lifetime models. The oldest and most used is the Taylor's model or modified Taylor's model. These models describe the relation between lifetime and the cutting parameters such as cutting speed, feed rate, and cutting depth. In the literature very few authors have introduced the wear in their model.

The model of Tsao et al. [22] takes into account the tool wear but does not include important machining parameters such as the feed rate and the cutting speed. It correlates the feed load to the tool wear and the damage of the material. Therefore, a machining quality criterion is used (maximum load allowed to ensure a certain quality). Lin and Ting [23] have proposed a model for monitoring the wear. The feed load F and the torque M are fitted as a function of the cutting parameters (cutting speed V_c, feed rate f (mm/rev) or feed speed V_f (mm/min), tool diameter d and wear W). The authors noted that the influence of wear on the feed load F is more important than the influence of the wear on the torque M. In other words, the recorded signal of the feed load is more sensitive to changes in the tool wear than the torque signal.

In this paper, a phenomenological model based on the evolution of the feed load (thrust force) with tool wear and composite damage is developed. The model takes into account the evolution of the feed load F with the feed rate f, the cutting speed V_c and the tool wear W. The cutting length L_c is the length of the path travelled by the tool tip when in contact with the composite material, so different from the machined length. Experimental work was also performed in order to validate the mathematical model. Experimental and model results are compared.

2. Experimental approach

2.1. Procedures and experiments performed

In order to establish the model, only parameters with significant effects on thrust force are included. In order to study the effects of cutting parameters and tool wear on cutting force signals, a series of experiments are conducted. Tests are carried out on a rigid instrumented drilling bench, with a power of 14 kW and a maximum rotation speed of 42,000 rpm, and a 5-axis FATRONIK-HERA machine with a power of 40 kW and a maximum rotation speed of 40,000 rpm.

The drilling bench is equipped with a high-speed spindle FISHER-MFW 1230/42. A HEIDENHAIN TNC 124 system control allows regulating the spindle rotation and the axial displacement of the bench. The experimental data were collected with a data acquisition system composed of a 9272 Kistler drilling dynamometer and a 5019 A Kistler amplifier, which allow to measure thrust forces. Average thrust forces for each test is estimated with

Table 1
. Drilling conditions and drilling sequence for tests on the drilling bench.

Test conditions	*Feed rate f* (mm/rev)	*Spindle speed N* (rpm)	*Cutting speed* V_c*(m/min)*
A	0.05	3000	56.55
B	0.05	6000	113.10
C	0.05	9000	169.65
D	0.05	12000	226.19
E	0.1	3000	56.55
F	0.15	3000	56.55
Drilling sequence : A B C D A E F A E F A E F A E F A E F A B C D			