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Mechanism for changes in cutting forces for down-milling of unidirectional carbon fiber reinforced polymer laminates: Modeling and experimentation

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ABSTRACT

In this study, a new cutting model for the machining of unidirectional CFRP laminates was developed to examine the mechanism for changes in the cutting forces with tool wear. This model is based on Zhang's model and divides the cutting zone into two characteristic deformation regions; chipping and pressing. Furthermore, CFRP milling tests were performed using two kinds of cutting tools: tungsten carbide (WC–Co) and polycrystalline diamond (PCD). Based on the experimental results with the developed cutting model, the net cutting forces to make a cut chip and press CFRP laminates under the flank surface of the tool were quantitatively evaluated. Consequently, it was found that the former does not depend on the progress of the tool wear, but the later increases with tool wear. Additionally, based on the results in this study, a new technique for reducing cutting forces during CFRP machining, which is based on the use of two layer tool that has a wear resistance distribution at around the tool edge was introduced.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) have excellent mechanical properties such as high strength-to-weight ratio, high modulus-to-weight ratios, a-high damping capacity, and good dimensional stability. Because of these advantages, CRRP composites are widely used for aerospace, automotive, robotics, construction, sporting goods, and medical and military applications; therefore, the use of CFRP composites is predicted to further increase in the future [1–3].

Machining techniques such as turning, milling and drilling are some of the most important processing method for CFRP composites; they are used to make complex shapes with accurate dimensions and high surface quality. However, CFRP composites are more difficult to machine than conventional metals. Their inhomogeneity, anisotropy, and abrasive nature cause rapid and severe tool wear, fiber pullout, and the occurrence of delamination and burrs. The understanding of deformation mechanisms for CFRP composites during mechanical processes is far from complete.

In general cases for the machining of CFRP composites, the increased cutting forces due to tool wear cause delamination and burrs, which drastically decrease the machined surface quality. In the past thirty years, several studies have been performed to predict the cutting forces during the machining of CFRP composites to examine the mechanism and determine the most appropriate machining conditions [4–14]. One of the most interesting results from these studies was that the machinability and tool wear processes strongly depend on the fiber-orientation relative to the cutting direction. Basically, investigating the cutting force characteristics have been provided essential knowledge for establishing CFRP cutting theories and developing for CFRP machining technologies.

This study, based on the cutting force prediction model developed by Zhang [9], proposes a simplified model for the machining of unidirectional CFRP composites. In the model, the machined material is divided into two characteristic deformation regions: chipping and pressing. In the chipping region, the removal material make a cut chip that flows over the rake surface of the tool. In the pressing region, the flank surface of the cutting tool presses the material under the tool. Thus, in the pressing region, the elastic or plastic reaction force and friction force work parallel and perpendicular, respectively, to the feed direction. Rough modeling assumptions were made to quantitatively evaluate the net cutting forces to make a cut chip and press the machined material. In order to experimentally obtain the net cutting forces, milling tests were performed on unidirectional CFRP composites using tungsten carbide (WC–Co) and polycrystalline diamond

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(PCD) tools under identical cutting conditions. Additionally, based on the estimation of net cutting forces, a new tool design criterion for reducing cutting forces during CFRP machining was introduced.

2. Modeling description

Fig. 1 illustrates the proposed CFRP cutting model. The model is based on Zhang's model [9]; some changes were made to simplify it for examine the cutting force characteristics. The model divides the cutting regions into two characteristic deformation regions: chipping and pressing.

In the chipping region, the deformation process is similar to normal orthogonal cutting with a very sharp cutting tool. The principal and thrust forces to make a cut chip F_{P1} and F_{T1} are described by the resultant force R:

$$\begin{aligned} F_{P1} &= R\cos(\beta-\alpha) \\ F_{T1} &= R\sin(\beta-\alpha) \end{aligned} \tag{1}$$

where α and β are the rake angle and the friction angle on the rake surface, respectively. The resultant force R depends on the fiber-orientation relative to the cutting direction θ, depth of cut a_c, and mechanical properties of the CFRP composites. Zhang et al. [9] presented a more detailed analysis to predict the theoretical value of R. However, this was outside the scope of this study; our focus was on estimating the experimental value of R as described in the following section. Note that the undeformed chip thickness t is nearly identical to the depth of cut a_c because CFRP materials are brittle [15]. Therefore, the shear plane angle is described by

$$\phi \approx \tan^{-1}\left(\frac{\cos\alpha}{1-\sin\alpha}\right) \tag{2}$$

In the pressing region, F_{T2} works to press the CFRP composite located below the flank surface of the tool; the material deforms elastically or plastically in the normal direction. Additionally, F_{P2} works as a friction force parallel to the feed direction. Using the Coulomb friction law with the friction coefficient μ, F_{P2} can be written as μF_{T2}. In order to generalize this expression, F_{T2} is replaced with the pressing force in the normal direction P. Consequently, the cutting forces F_{P2} and F_{T2} are written as

$$\begin{aligned} F_{P2} &= \mu F_{T2} = \mu P \\ F_{T2} &= P \end{aligned} \tag{3}$$

Note that the value of P strongly depends on the mechanical characteristics of the CFRP plate and shape of the cutting tools. In this study, as was the case for R, the value of P was experimentally estimated; this is discussed in the following section.

The total forces in the X and Y directions acting on the cutting region, i.e., F_X and F_Y, are the summation of the cutting forces in the two regions. They are described by

$$\begin{aligned} F_P &= F_{P1} + F_{P2} = R\cos(\beta-\alpha) + \mu P \\ F_T &= F_{T1} + F_{T2} = R\sin(\beta-\alpha) + P \end{aligned} \tag{4}$$

Thus, the net cutting forces R and P can be described by solving the two parts of Eq. (4) simultaneously:

$$R = \frac{F_P - \mu F_T}{\cos(\beta-\alpha) - \mu\sin(\beta-\alpha)} \tag{5}$$

$$P = \frac{F_P\sin(\beta-\alpha) - F_T\cos(\beta-\alpha)}{\mu\sin(\beta-\alpha) - \cos(\beta-\alpha)} \tag{6}$$

Note that the cutting forces F_P and F_T can be easily measured in experiments. Thus, based on the developed CFRP cutting model (i.e., Eqs. (5) and (6)), the net cutting forces can be experimentally obtained.

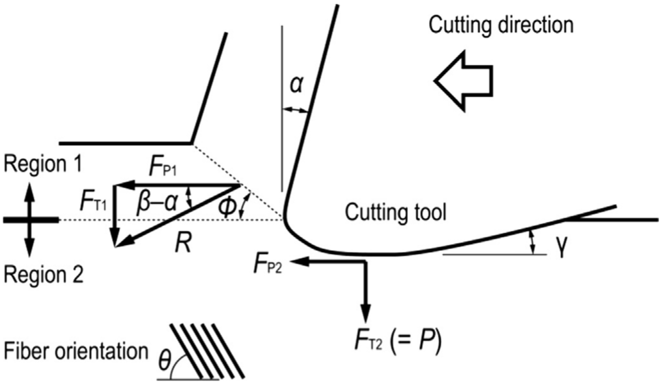

Fig. 1. Developed model to predict cutting forces of orthogonal cutting with unidirectional CFRP composites: α=rake angle, β=friction angle on the rake surface, γ=flank angle, θ=fiber-orientation relative to cutting direction, R=resultant force, P=pressing force.

The measured changes in the net cutting forces with the progress of the cutting tool wear are an important to understanding the machining mechanism for CFRP composites. In this study, in order to collect data on the changes in the cutting forces F_P and F_T, milling tests were performed for unidirectional CFRP composites using two kinds of different cutting tools. Based on the measured data and Eqs. (5) and (6), the changes in the net cutting forces with tool wear can be evaluated.

3. Experimental procedure

Fig. 2 shows the details of the experimental setup. The cutting tool was fixed to the tool jig via the tool folder, and the tool jig was rotated by the main spindle of the machining center with a constant rotating speed (Fig. 2(a) and (b)). A unidirectional CFRP plate was fixed on the stage of the machining center via a steel vise. Fig. 3 shows a schematic configuration for a single pass in the plane down-milling test, along with the geometry of the cutting tool and the orientation of the carbon fibers of the CFRP plate. The cutting conditions were set as follows: a cutting speed V of 30 m/min, feed rate f of 0.05 mm/rev, radial depth of cut d of 2.0 mm, and fiber orientation θ of 0° and 90°. The cutting forces F_P and F_T are the principal and thrust forces, respectively. They are calculated from the cutting forces in the X and Y directions as measured by the dynamometer:

$$\begin{aligned} F_P &= F_X\cos\varphi + F_Y\sin\varphi \\ F_T &= -F_X\sin\varphi + F_Y\cos\varphi \end{aligned} \tag{7}$$

where φ is the engagement angle. The undeformed chip thickness t and carbon fiber orientation against the feed direction θ varies continuously with the changing angle φ. The changes in t are described by the angle φ as follows [16]:

$$t = f\sin\varphi \tag{8}$$

where f is the feed per tooth, which was set to 50 μm.

In general, multidirectional CFRP composites are more commonly used than unidirectional CFRP composites. However, the interaction between cutting tools and unidirectional composites is easier to examine because their mechanical properties and machining characteristics are simple relative to those of multidirectional composites. Therefore, unidirectional CFRP plates were used as work specimens in this study. The carbon fibers and prepreg were 8.0 μm in diameter and 200 μm in thickness,