CHARACTERIZATION OF DYNAMIC FORCES IN ORTHOGONAL CUTTING OF CFRP

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Abstract

This work deals with the characterization of the dynamic cutting forces and the chip formation in the orthogonal cutting of CFRP. The time series of the dynamic cutting forces are acquired by a force sensor. In experiments, relatively stable and undulate type force signals are observed for different fiber orientations. Chip formation mechanism is discussed based on the in-situ observation. There are three types of chip formation for different cutting angles: Delamination-dominant, Bending-dominant, Cutting-dominant. Furthermore, the dynamic signals are processed by the Fast Fourier Transform technique to study the frequency spectrum features for different cutting angles. The chipping time is calculated by the characteristic frequency of the cutting force. The chipping time for 135° cutting angle is the longest with the largest force amplitude. Finally, the failure processes in chip formation are discussed based on the local characterization of the cutting force.

1. Introduction

Carbon-fiber-reinforced plastic (CFRP) provides superior properties of high strength-to-weight ratio, high modulus-to-weight ratio, high damping capacity, and fatigue resistances compared with glass-fiber-reinforced plastic (GFRP) [1]. CFRP is widely used in aerospace, robotics and military applications [2]. Although CFRP is usually fabricated to near net shapes by autoclave molding [3], the post machining operations are necessary to assure the dimensional tolerance, surface quality and other functional requirements [4], such as trimming of outer profile, drilling and milling of large-diameter holes. Due to the characteristics of non-homogeneity and anisotropy, delamination and burrs come into being easily in these machining process, which can seriously influence the performance of CFRP structures.

Because a CFRP part consists of multiple different oriented unidirectional layers, the cutting edge will contact various oriented layers at the same time and cut fibers at any angle within one revolution in the milling and drilling operations. Thus, the essence of machining CFRP is the material removal of unidirectional CFRP (UD-CFRP) at different fiber orientations. Machining experiments of CFRP have been conducted in literature to investigate the chip formation. Firstly, it is found that tools with positive rake angle are common in the literature. Meanwhile, the exprimental results reveal the tool with a wedge angle of approximately 75° and a rake angle of 0° to 7° is favorable for machining CFRP [5]. Then, the chip formation and cutting force strongly depend on the angle between the fiber orientation and the cutting velocity vector. The morphology of machined surface could give evidence of the chip formation mechanism as well as the subsurface damage [6,7]. Two basic failure mechanisms at macro level have been recognized: shearing in the perpendicular direction and buckling

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in the parallel direction [8]. Examination of the chips indicates that they have not been subjected to large deformation, and the cutting process consisted of a series of fractures. In addition, the in-situ observation is also used to investigate the chipping process [9]. There are three types of chip formation: delamination, fiber buckling and fiber cutting types by SEM observation of the chip geometry and machined surface, which are determined by the fiber angle and the rake angle.

Cutting forces are the basic physical quantity that can embody the relevant process information in machining. Such information can be used to assist in understanding the machinability, the tool wear or fracture and the surface finish [10,11]. The sensory feature of cutting forces is decomposed into measurable components in order to determine the time-domain characterization. Thus, the relations with the other relevant variables can be quantified. Generally, the average values of the cutting forces through the whole cutting process should be studied. It is observed that the average cutting force in orthogonal cutting rises with the fiber orientation angle increasing from 0° to 90° and, falls with the decreasing from 90° to 180° [6,7] However, the chipping process is discontinuous due to the non-homogeneity of CFRP. The continuous change of the cutting forces corresponding to one single chip formation are very different in machining of CFRP at different orientations. The features in the time domain and the frequency domain of the cutting forces are widely studied in metal cutting, and they provide alternatives to investigate the cutting process in detail. Frequency analysis of the cutting forces is discussed by Rumula [12] in orthogonal cutting of GFRP. The results reveal that the FOA (Fiber Orientation Angle) and the tool rake angle have significant effects on the cutting mechanism, and the effective fiber orientation angle is consistent with the cutting mechanism involved. However, there is few investigation on the characteristics of the cutting forces in machining of CFRP to study the chip formation mechanism.

This work carries out the orthogonal cutting experiment of UD-CFRP. The signal of the cutting forces and chipping process are measured. Based on the measurements, the features in time domain and frequency domain of the cutting forces are investigated. The chipping time is calculated by the characteristics. Furthermore, the relations between the chip formation and the local characterization of the cutting force are analyzed.

2. Orthogonal cutting experiments

2.1. Experimental setup

Experiments of orthogonal cutting of UD-CFRP are performed on a planning unit. This unit is equipped with a linear motor with a resolution of μm. The work piece is clamped on the working table as shown in Figure 1. A linear motion providing by the motor can obtain a steady cutting status. The cutting tool is fixed on the dynamometer table. Cutting forces are measured by a six-dimensional dynamometer Kistler 9257B. In addition, the cutting processes are recorded by a high-speed camera with a micro lens.

Cutting tools used are made from tungsten carbide with 5° clearance angle and 25° rake angle. Unidirectional carbon fiber (T800) prepregs are used to make the CFRP panels for the work piece. The panels are laid-up by 24 plies with ply thickness of 125μm, and solidified in autoclave under pressure of 0.62MPa. Using an slot saw and diamond impregnated wheel, the panels are fabricated into specimens of two fiber orientations: 0°, 45°and desired dimensions 100mm×40mm×3mm. The angle between the fiber orientation and the direction of cutting speed is defined as the cutting angle θ as shown in Figure. 2. Orthogonal cutting experiments are performed with different cutting conditions are listed in Table 1.

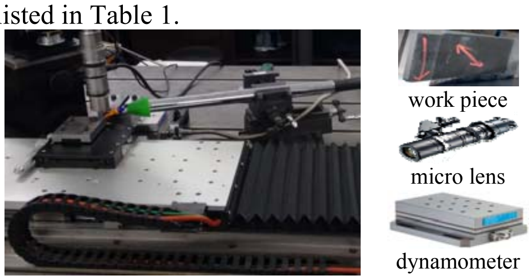

Figure 1. Facilities of orthogonal cutting.

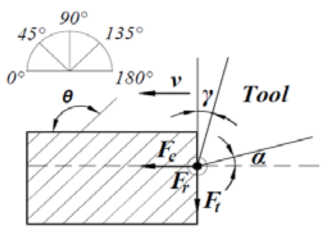

Figure 2. Definition of the cutting angle (θ).

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Table1. Operation conditions of experiment

Parameters		
UD-CFRP	Dimension/mm	100×40×3
Tool geometry parameters	Rake angle γ/(°)	25
	Relief angle α/(°)	5
	Edge radius/μm	10
Cutting conditions	Cutting depth a_c/μm	50
	Cutting angle θ/(°)	0,45,90,135
	Cutting speed V_c(mm/min)	500

3. Machining Experiments, Analysis and Discussions

3.1. Machining Response

The chipping processes are observed as shown in Figure 3, and the chipping formation types are summarized as follows.

Delamination-dominant chips followed by bending: for 0° cutting angle as shown in Figure 3(a), the tool cuts so easily into the laminate, and then the layer is peeled in the cutting plane and to slide on the rake face to bend. Chip breaks off perpendicularly to the fiber axes at the end of delamination path. Elastic deformation of fibers is considerably large for bending just as a cantilever beam due to the tool advancing [13].

Bending-dominant chips followed by shear: for 135° cutting angle, the rake face of tool contacts the materials firstly as shown in Figure 3(c), and then the materials bend forward with larger elastic deformation owing to the serious cracks along the fiber orientation under the machined surface. Subsequently, the cutting edge contacts and crushes the materials. In this case, the chipping with shear occurs. Furthermore, the work piece is split off easily along the fiber owing to the large bending deformation.

Cutting-dominant chips: for 45° and 90° as shown in Figure 3(b, d), chipping along an overall shear plane occurs under the compression of the cutting edge. Cracking extends along the shear plane until the chip is separated from the work piece with the advance of the rake face. The vibration of chipping is quite obvious by the in-situ observation.

Time series of the cutting forces are shown in Figure 4. By observing the figure, the delamination-dominant (θ=0°) and the cutting-dominant type (θ=45°) chip formations exhibit the steady processes. However, the cutting-dominant type (θ =90°) chip formation exhibit a very fluctuant processes as shown in Figure 4(c).

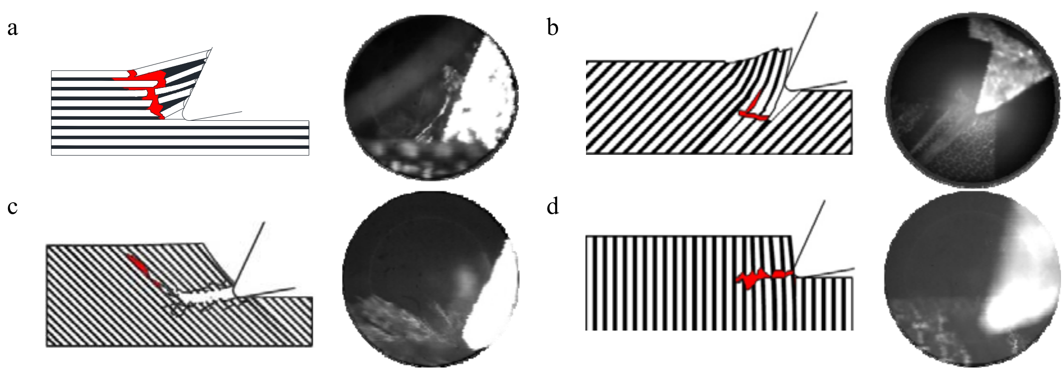

Figure 3. Chipping by in-situ observation

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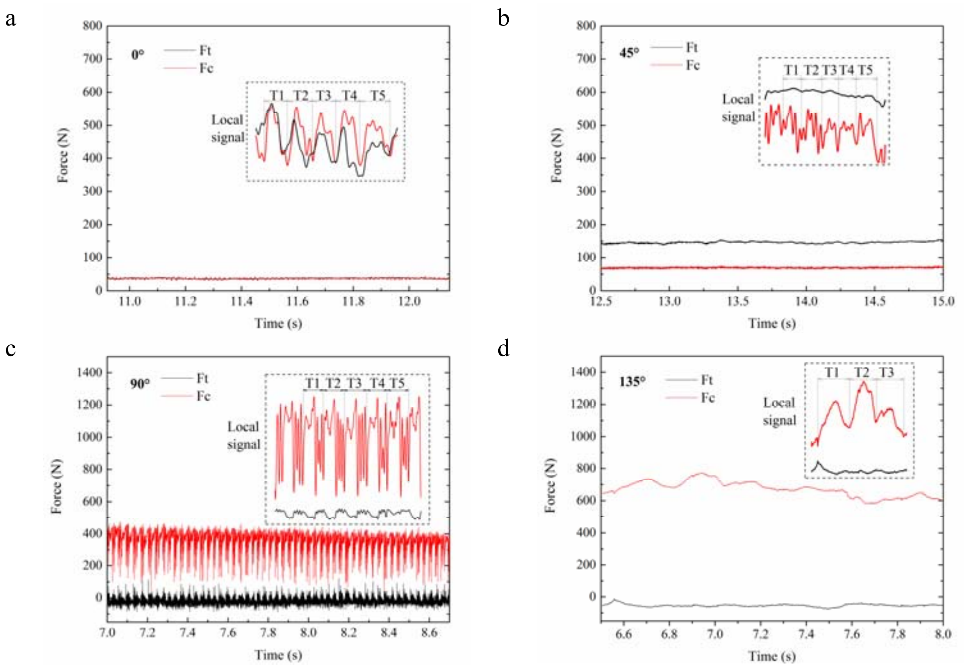
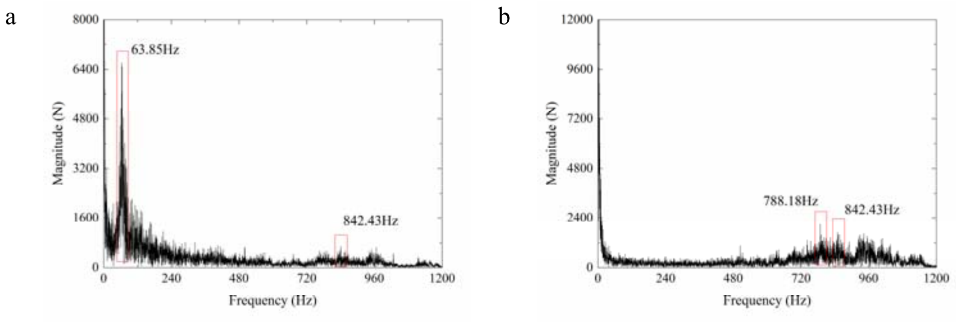


Figure 4. Time series of cutting forces for different cutting angles

3.2. Frequency-domain Characteristics of Cutting Forces

Fluctuation of the cutting forces in the local periods of chip formation reveals the process of the local failure at micro level. The local failure during the chip formation includes the fracture of brittle fiber and matrix, and the interface debonding. Particularly, the fracture of fibers is dominant, and there is a fundamental frequency determined by the cutting time of a unit cell consisting of fiber and matrix. As shown in Figure 5, results of frequency spectrum reveal the fundamental frequency of this operating condition is 842.43 Hz. The peak features in low frequency spectrum of the cutting force is distinct for 0°, 90°, and 135° cutting angles. Consequently, there is only one characteristic frequency for 0° and 135° cutting angles, but two frequency peaks for 90° cutting angle. However, there is only high frequency peak appears for 45° cutting angle. In case of the cutting-dominant type chip formation, the maximum value of the cutting force for 90° cutting angle is obviously larger than that for 45° cutting angle as shown in Figure 4 accordingly. The reason is that there is a longer chipping time for 90° cutting angle as shown in Table 2. Meanwhile, the cutting force is the largest with the longest chipping time for 135° cutting angle. In addition, the magnitude of the cutting force corresponding to the fundamental frequency for bending-dominant type (0°) and delamination-dominant type (135°) is far less than that for cutting-dominant type (45° and 90°).



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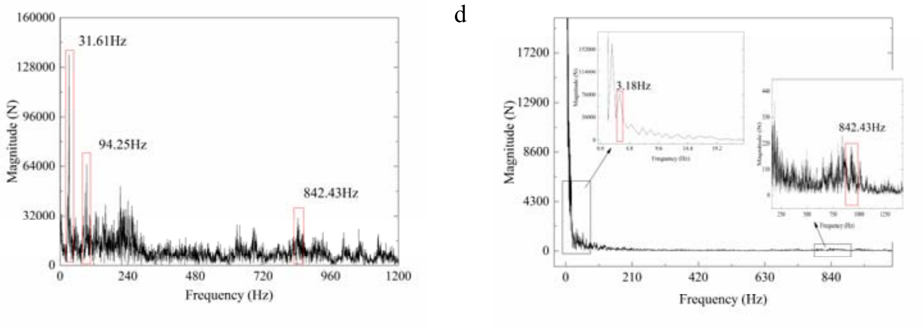

Figure 5. Frequency spectrum for different cutting angles

Table 2. Chipping time for different cutting angles.

Cutting angle (°)	0	45	90	135
Frequency (HZ)	63.85	788.18	31.61	3.18
Chipping time (s)	0.0157	0.0013	0.0316	0.3144

3.3. Failure Process in Chip Formation

Curves of the cutting forces in one chip formation for 0°, 45°, 90°, and 135° cutting angles are show in Figure 6. The change of the cutting forces is corresponding to the failure process of fibers, matrix and interface at the micro level. For 0° cutting angle, it represents a delamination-dominant type. During the chipping, fibers are crushed firstly by the cutting edge. Stage 1 of the curve of the cutting force is corresponding to the process of the Mode I fracture and bending as shown in Figure 6(a). Because relatively little fractured surface is generated and the toughness is low for Mode I fracture [14], it initiates and extends easily along the interface quickly under the opening loading by the cutting tool. Accordingly, the fibers bend with feed of the tool. Subsequently, due to the lower strength of carbon fibers in compression relative to their tensile strength, flexural failure usually initiates on the compression face of the material in this bent status [15]. Thus, the compression failure of fibers occurs at the end of Stage 1. With the advance of tool, the fracture propagates from the tensile face towards the compression face in Stage 2. Finally, the material is peeled off from the work piece. The elastic deformation of the fiber is considerably large for bending with the tool advancing just as a cantilever beam [13]. Thus, sheet-like chips are generated.

Figure 6 (b) shows the change of the cutting force in one chip formation for 45° cutting angle. The tiny waves of curves reveal that the fibers are cut off under shearing one by one until the matrix cracking along the fiber orientation. After several fibers cut off, the initial cracking corresponds to the moment of the highest force value in Stage 1. However, the fibers are cut only by the cutting edge, and this is equal to cutting fiber by a tool with a nearly 90° rake angle. In this case, the material is under Mode II loading, and the matrix fractures that they develop at an angle to the laminate plane need more energy. Thus, the fracture of matrix only occurs in the local area of tool-material contact, and it does not extend to the upper area. There is no matrix crack along the fiber orientation for chip separating under the condition. Finally, the continuous chips are generated.

However, for 90° cutting angle as shown in Figure 6 (c), there are three segments of force signals corresponding to the three chip formations under compression. Then, the increasing process in Stage 2 corresponds to the formation of the shear plane while the tool cutting into the material. The length of the plane for one chip formation is determined by the strength of the interface, depth of cut, edge ratio, and the cutting speed. With the tool cutting into the material, the chip is pushed by the rake face. During this process the Mode I fracture occurs, and the chip separates from the work piece when the force reaches its maximum value in Stage 2. As discussed above, the magnitude of the cutting force corresponding to the fundamental frequency in the frequency spectrum is the largest, which is caused by Mode II fracture of the matrix in local area of the tool-material contact.

For 135° cutting angle, there is a long bending process in chipping corresponding to Stage 1 as shown in Figure 6 (d), because the larger elastic deformation is needed for bending along the depth of cut.

However, fibers does not fail in this bending state. Thus, the cutting edge have to contact fibers for cutting after enough bending deformation at the beginning of stage 2. Consequently, the fibers are cut off by the cutting edge. In addition, the tiny fluctuations of cutting forces represent Mode I fracture of the matrix under the opening load due to the bending deformation. In case of 90° and 135° cutting angles, the mechanism of fiber cutting can be investigated as an elastic foundation beam model [16], which indicates the cutting force is larger than the other due to the strong support effect.

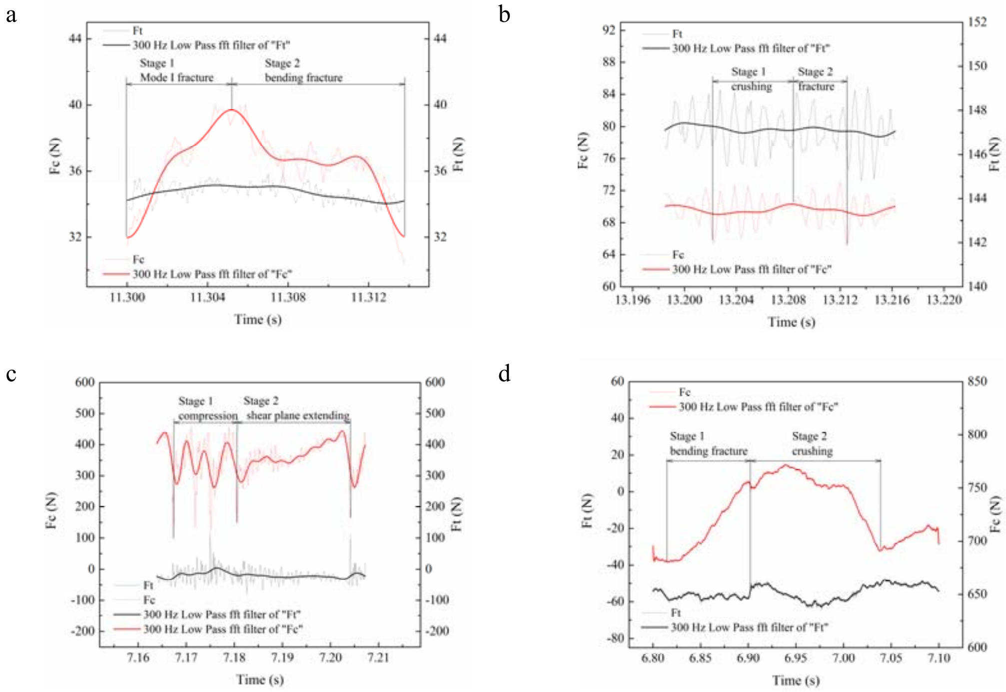

Figure 6. Typical curve of cutting forces in single chip formation: (a) θ=0°, (b) θ=45°, (c) θ=90°, (d) θ=135°

4. Conclusions

There are three types of chip formation for different cutting angles: Delamination-dominant, Bending-dominant, Cutting-dominant in machining of CFRP material. The chipping time is important to quantify the chip size for predicting the cutting forces. In this study, the chipping feature can be recognized from the characteristic frequency of the cutting force signal via frequency spectrum analysis. The chipping time for 135 cutting angle is the longest and the corresponding cutting force is the largest among the four cases. For 45° and 90° cutting angles, the low frequency feature corresponds to a longer chipping time for cutting-type chip formation. The length of shear plane for 90° cutting angles can be predicted by the time of Stage 2. The magnitude analysis reveals that more energy is required for matrix fracture for the cutting-dominant type chip formation.

Acknowledgments

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