PERFORMANCE OF BRAZED DIAMOND TOOL IN GRINDING OF CARBON FIBER REINFORCED POLYMER LAMINATES

Yuhong Liang , Yan Chen*, Yucan Fu, Chaoren Yan, Kai Zheng

College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, PR China
*Correspondence: ninaych@nuaa.edu.cn

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ABSTRACT

Carbon fiber reinforced plastic (CFRP) is widely used in the aerospace industry due to its high specific strength and elastic modulus. Grinding is supposed to be an effective process and can provide longer tool life, according to its machining property. However, the poor chip-removing during grinding is still a considerable problem. In this investigation, a monolayer brazed diamond tool was developed and a study on tool performance during grinding multidirectional CFRP laminates was presented. The influence of machining parameters and cutting length on grinding force were investigated. The surface morphologies of the workpiece were examined by scanning electron microscope (SEM) with the fiber cutting angles of 0˚, 45˚, 90˚, and 135˚, respectively. The results indicated that grinding force would be higher when feed rate and depth of cut increased and the main wear modes of tool were attritious wear or micro-fragmentation. Meanwhile, the fibers were removed cleanly as a result of fracture by pressing and buckling for the fiber cutting angle of 0˚. Additionally, matrix smearings were detected at the fiber cutting angle of 90˚. Moreover, the minor cavities were observed with the fiber cutting angle of 45˚and 135˚.

1 INTRODUCTION

Carbon fiber reinforced polymer (CFRP) has attracted widely attention in the aerospace industry, considering its superior mechanical properties, such as high specific strength, light weight [1, 2]. However, the machining of CFRP is considerably difficult compared with the machining of conventional metals due to anisotropic properties, non-homogeneous, high stiffness and poor thermal conductivity. The poor machinability of CFRP usually manifests various machining defects including delamination, fiber pullout, burrs and thermal degradation [3-5].

Janardhan points out that tool wear is the main reason which will result in the machining damage of CFRP. The small plastic deformation and high hardness of carbon fibers will cause severe tool wear, which would result in low accuracy, poor surface quality and high machining cost [6]. In order to improve the CFRP machining quality, several kinds of tools were developed [7, 8]: (a) cutting tool with polycrystalline diamond (PCD) inserts; (b) the solid carbide endmill coated with a diamond coating; (c) diamond interlocking "burr" router tool with several helices right-hand and several others left-hand. Abrasive tools are also applied in machining CFRP because of the less mechanical damage and better surface finish [9].

It is commonly believed that the grinding is supposed to be an effective process according to its machining property [10, 11]. Soo et al. [12] proved that greater levels of tool wear, cutting force and workpiece surface roughness were experienced when tools employing CBN compared to diamond abrasives in edge routing of CFRP laminates. Additionally, grinding with diamond (grit size 76 μm) produced an understandably lower roughness of ~3.0 mm Ra after a 9.6 m cut length. Tsao [13] compared the effect of two drill geometries, i.e., the core-saw drill and the core drill and concluded that the core-saw drill was less susceptible to causing delamination due to the larger critical thrust force.

The cutting force is considered to be one of the most important factors associated with the tool wear. Many investigations had been carried out to understand the cutting force in CFRP machining. Slamani [14] developed two models to predict tool wear and cutting force for different values of cutting speed, feed and cutting length. The results showed that a higher tool wear was associated with

the higher level of feed rates and lower level of cutting speed. It was found also that the cutting force and tool wear were high in low ratio of cutting speed to feed rate. Huda [15] investigated the effectiveness of ultrasonic assisted grinding in terms of tool condition, cutting forces and surface integrity in comparison with conventional grinding of CFRP. Liu [16] developed a rotary ultrasonic grinding force model based on CFRP and conducted grinding test using grit size diamond, and experiment results indicated that grinding force will remain substantially unchanged as grit size (mesh #) increases, because if grit size increased, the abrasive size decreased and number of active abrasive grains increased, which caused little change in grinding force.

Moreover, cutting force and surface quality are highly dependent on tool and fiber cutting direction [17, 18]. Karpat [19] proposed mechanistic cutting force model for milling of CFRP laminates. They observed that radial forces peak for the 0 ° fiber direction were higher than the radial forces measured on 45 ° fiber directions. The greatest tangential forces were observed when machining laminate of 135 ° fiber direction, the smallest tangential forces were observed on 45 ° fiber direction.

Nevertheless, the previous researches on grinding of CFRP are focused on undefined distributed grinding tools. The poor chip-removing and serious tool clogging will affect the grinding behaviour. It is noted that the defined distributed of diamond grains on the tool could provide more inter-grit chip space and higher grain protrusion, which is benefit for CFRP grinding process. In this study, the effects of cutting parameters (cutting speed, feed rate and depth of cut) and cut length on cutting force were investigated. Meanwhile, the main wear modes of brazed diamond tool and surface morphologies were discussed in the grinding.

2 EXPERIMENTAL DESIGN AND PROCEDURE

The grinding experiments were carried out in a DMG high-speed machining center (Fig.1(a)). A brazed diamond grinding tool was fixed on the holder. The workpiece was mounted on a dynamometer, which was fixed to the machine platform. The machining forces during grinding experiments were measured by a Kistler 9272 3D dynamometer and its Kistler 5070A charge amplifier. The workpiece material was T700 CFRP, in which the volume ratio of carbon fiber was 60%. The dimension of the workpiece was 200 mm×150 mm×3 mm. The fibers were manually laid up in a repeating sequence of orientatione 0 °/90 °/0 °/45 °/135 °/90 °/0 °/45 °/135 °/90 °. The experimental investigation was performed with supplying of coolant.

Due to the high specific strength of CFRP and particular characteristic of CFRP chip, a monolayer brazed diamond tools with defined grain distribution and great grain exposing height were developed with long 60mm and diameter 6 mm (Fig.1(b) (c)). The brazed diamond grinding tool parameters and detail tool parameters were listed in Table 1. The monolayer brazed grinding tools used in test were manufactured at the brazing temperature in vacuum brazing operation, which use a bonding layer, e.g. the Ag–Cu–Ti alloys, as a joining material to form a strong chemical bond between the diamond grains and metallic matrix. Furthermore, tool topography was optimized in relatively regular grains distribution. The brazed diamond tool could provide more inter-grit chip space and higher grit protrusion in comparison with the electroplated ones which kept the tool free of loading during grinding with high material removal rate [20]. Moreover, the brazed ones offer total flexibility to control the spacing between the grains, which made this class of tools more promising. The tests were conducted with brazed diamond tool by down-grinding to evaluate the grinding performance.

Tool matrix	Diameter/mm	Length /mm	Abrasive particle size /μm	Brazing filler metal	Helical angle	Rows
WC	6	60	150-160	Ag-Cu-Ti	45°	16

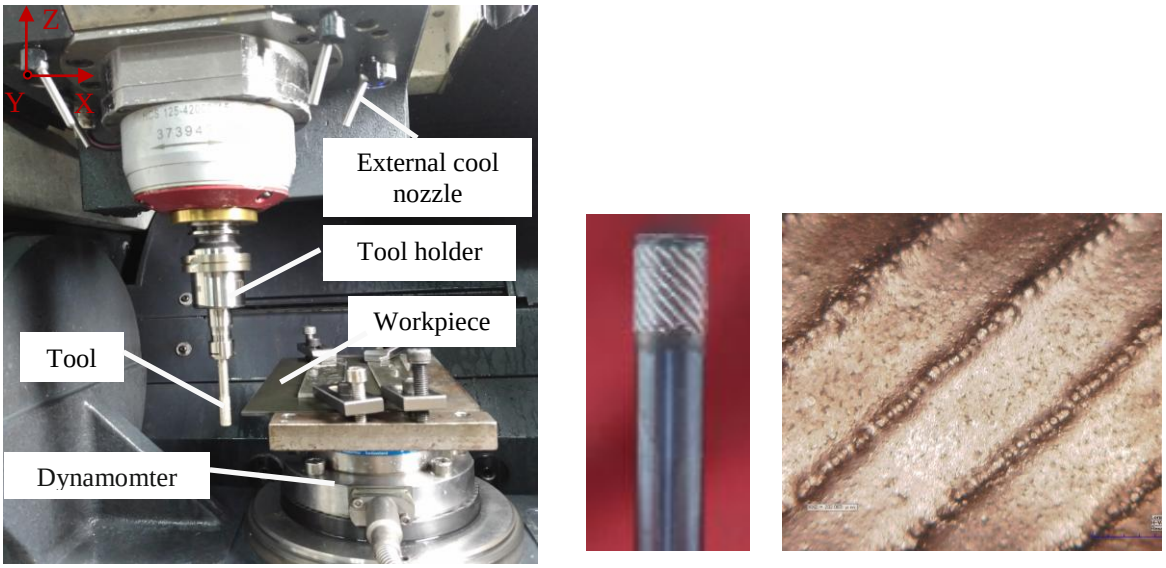
Table 1 Brazed diamond grinding tool parameters

3 RESULTS AND DISCUSSION

3.1 Parametric Influence on grinding force

The cutting forces generated during the grinding process were due to various cutting parameters. In order to minimize the number of tests required, Taguchi (L9 array) experimental design method was

employed. Three levels of cutting speed, three levels of feed speed and three levels of redial depth of cut were used. The machining parameters used in the grinding experiments are listed in Table 2.



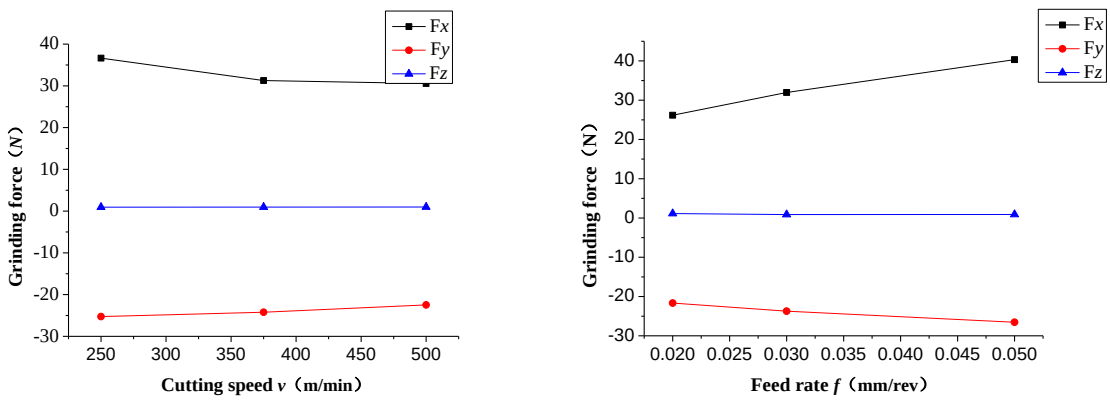
(a) (b) (c)

Fig.1 Experimental arrangement and tool
(a) experimental arrangement; (b) the brazed diamond tool; (c) tool morphology

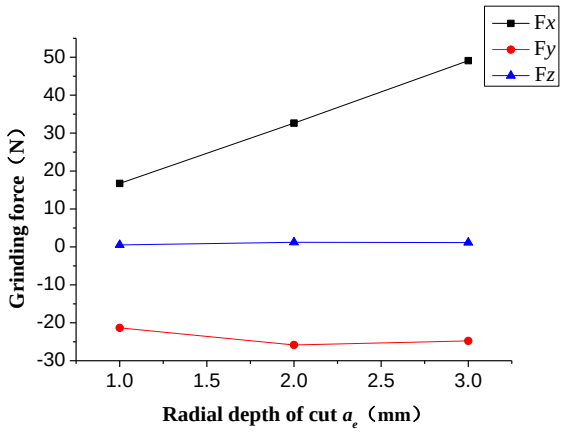
Grinding parameters	Levels
cutting speed v (m /min)	250、375、500
Feed rate f (mm/rev)	0.02、0.03、0.05
Redial depth of cut a_e (mm)	1、2、3

Table 2. Machining Parameters

Fig. 2 exhibits the influence of grinding parameters on grinding force. The results indicate that the grinding force increase with the raising of feed rate and radial depth of cut. This is due to the increase in the cross-sectional area of the undeformed chip. The observed reduction in grinding force with increasing cutting speed is due to stabilized cutting action and to a possible increase in the heat generated, which facilitates thermal softening of work material leading to reduction in the resistance forces. Meanwhile, the radial depth of cut has great effects on grinding force compared with cutting speed and feed rate.



(a) (b)



(c)

Fig.2 The influence of grinding variables on grinding force(a) grinding force versus the cutting speed;(b) grinding force versus the feed rate; (c) grinding force versus the radial depth of cut

3.2 Tool wear

Tool wear is the dominant phenomenon which will affect the CFPP surface quality. Wear tests were performed to estimate the tool life with the optimal grinding parameters identified during first set of machining experiments. In addition, in order to evaluate the influence of tool wear on machining quality and grinding force, and to identify tool wear mechanisms, grinding force measurement were conducted in function of cutting length. The grinding force at v =375 m/min, f =0.05 mm/rev and a_e=1 mm of the experimental CFRP was illustrated in Fig.3. It can be clearly observed that the grinding force increases steadily with cutting distance because of tool wear. When cutting length increased to 15000mm, the main grinding force only increased by 56%.

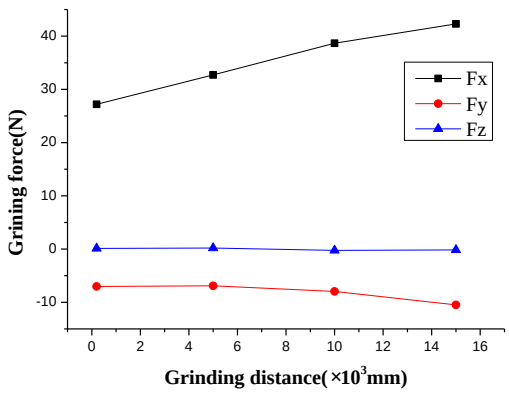


Fig.3 The graphs of grinding forces on different grinding distance

It is necessary to inspect the tool wear modes in grinding CFRP. Fig. 4 displays the micrographs of tool surface in the whole grinding process. It can be clearly seen that the initial status of grains. As seen from Fig. 4 (b), it is obvious that there was few wear of grain after 5000mm cutting length. However, after 10000 mm cutting length (Fig. 4(c)), the slight grain attritious wears were observed in grinding. Besides, as the cutting length was increased to 15000 mm, the grain micro-fragmentation was observed obviously in grinding due to the continuous impacts on the workpiece and grains. The topographies observations indicated that no diamond grain pull-out of the bonding agent were found during the whole grinding process and the chip adhesion rarely appeared. Generally, wear modes of diamond grains may belong to attritious wear and grain fracture for the whole process. The results indicated that no macroscopic machining damages were observed when a further 15000 mm cutting length was completed. The defined distributed brazed diamond tool was suitable for cutting multidirectional CFRP laminates

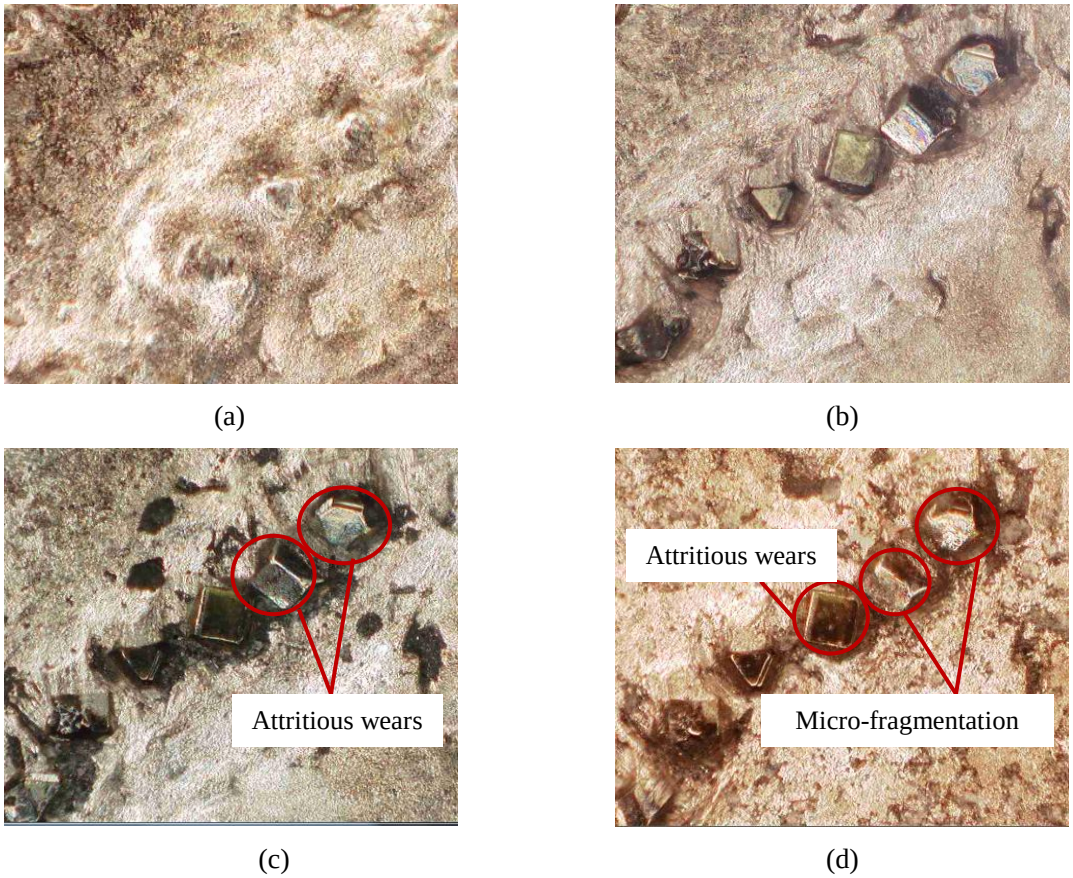


Fig.4 The micrographs of tool surface in the whole grinding process
(a) tool initial morphology; (b) tool morphology after 5000mm cutting length;
(c) tool morphology after 10000mm cutting length; (d) tool morphology after 15000mm cutting length

3.2 Surface morphologies

The performance of a tool can be evaluated either in terms of tool life or surface morphologies during whole grinding process (Fig. 5). It can be seen that significant damage did not appear with the increase of cutting length. However, there exist more groove scratches in the grinding process. This is much different form the results other machining process such as drilling and milling. This is due to the fact that the grinding is a multipoint cutting process which has a myriad of micro-cutting edges with different negative rake angles.

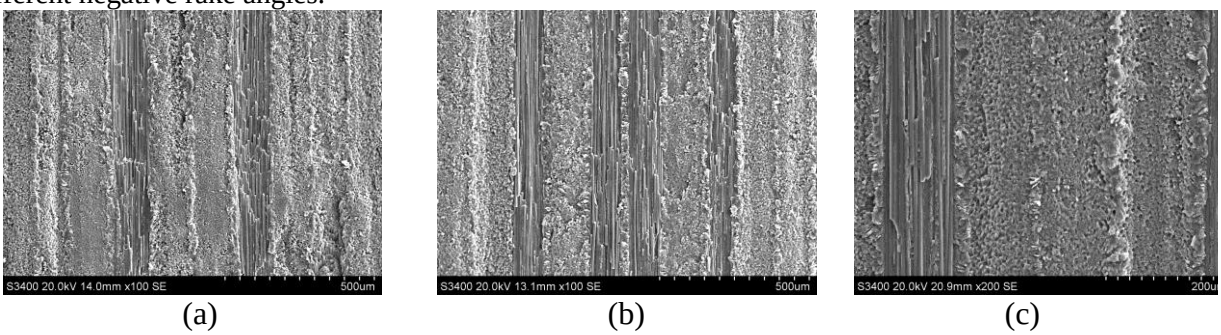
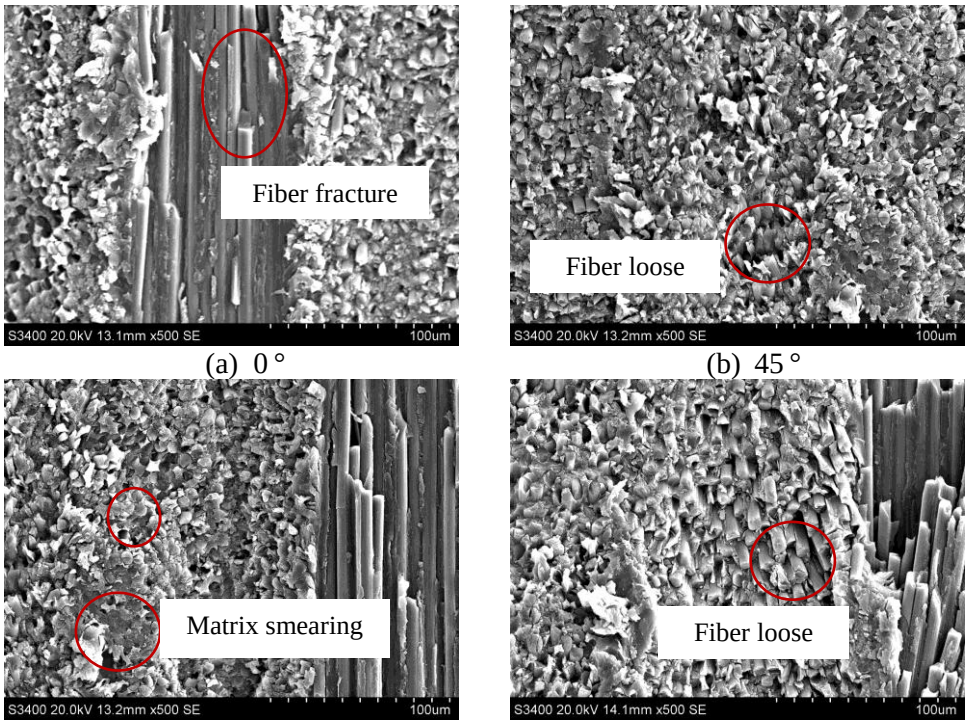


Fig 5 The surface micrographs of CFRP in the whole grinding
(a)surface micrograph after 5000mm cutting length; (b) surface micrograph after 10000mm cutting length;(c) surface micrograph after 15000mm cutting length

Depending on the fiber cutting direction, the material removal mechanisms and surface morphologies have great difference during cutting of CFRP laminates. Fig.6 illustrated the SEM

(scanning electron microscope) micrographs of CFRP obtained after grinding with conventional machining using a brazed diamond tool at different fiber directions. It was observed that fibers were removed cleanly as a result of fracture by pressing and buckling at the fiber cutting angle of 0˚. Whereas, fibers with 0˚ removed cleanly as a result of fracture by buckling in milling. Moreover, flaws in terms of fiber/matrix loose were apparent, particularly for the fiber cutting angle of 0˚ 45˚and 135˚ direction due to fiber bending and fracture. Surprisingly, no major defects and minor cavities were observed at the fiber cutting angle of 45˚and 135˚. In addition, matrix smearing can also be detected at the fiber cutting angle of 90˚. This was similar to observations described by El-Hofy et al. [21] when routing equivalent CFRP material using polycrystalline diamond.



(a) 0 ° (b) 45 °

(c) 90 ° (d) 135 °

Fig 6 SEM micrographs of surface morphologies at different fiber cutting directions

3.3 Machining accuracy

In order to completely evaluate performance of the brazed tool, the machining slot (width 6mm) tests were carried out in grinding process. The Fig.7 illustrated the geometry size of slot measured under the microscope. It can be observed that the dimension was decrease with the increase of cut length due to the decrease of grain protrusion. The size tolerance of slot was ±0.1mm.

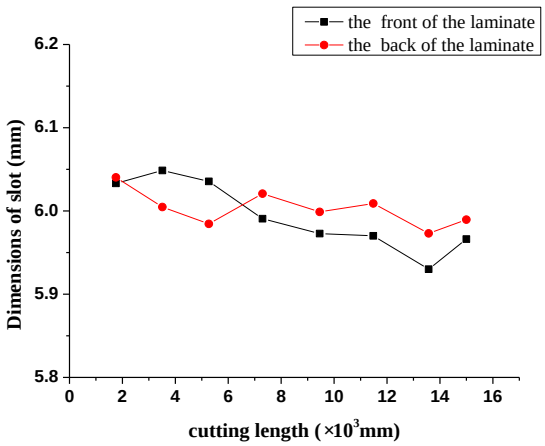


Fig.7 The geometry dimension of slot

4 CONCLUSIONS

The experiments conducted in this work involved grinding of CFRP laminates with the brazed diamond tool under different conditions of spindle speed, feed rate and grinding distance. The effects of cutting parameters on cutting force were investigated. The geometry accuracy of slot was measured under the microscope. The performance of the tool was evaluated in terms of grinding force, cutting length and surface micrograph during grinding of CFRP. Some important results have been concluded as follows:

(1) The defined distributed brazed diamond tool was more suitable for cutting multidirectional CFRP laminates. The brazed diamond tool can provide more inter-grit chip space and better chip-removing.

(2) The main cutting force increased with the raising of feed rate and cutting depth when the spindle speed was kept constant in grinding of CFRP laminates. In addition, the cutting forces increased as the grinding distance increased owing to the tool wear.

(3) The brazed diamond tool had higher tool life due to the high hardness and brazing technology. The main wear modes of brazed diamond tool were attritious wear or micro-fragmentation when the edge grinding distance reached 15m.

(4) The surface morphologies were examined by SEM at fiber cutting direction of 0˚, 45˚, 90˚, and 135˚. It was found that the fibers were removed cleanly as a result of fracture by pressing and buckling for the fiber cutting angle of 0˚. Additionally, matrix smearings were detected at the fiber cutting angle of 90˚. Moreover, the minor cavities were observed with the fiber cutting angle of 45˚and 135˚.

(5) In order to completely evaluate performance of the brazed tool, the geometry size of slot was measured under the microscope. The size tolerance of slot was ±0.1mm.

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