# Influence of Angle Between Fibre and Machining Direction for CFRP Machining Using cBN Electroplated End-mill

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**Keywords:** carbon fibre reinforced plastic (CFRP); cubic boron nitride (cBN); electroplated end-mill; fibre direction

**Abstract.** The demand for CFRP has recently increased in various fields. Thus far, few studies have investigated the quality of the machined surface, the degradation of CFRP mechanical properties with machining temperature, and the cost of machining tools. For this study, we have developed a cubic boron nitride (cBN) electroplated end-mill. This tool can be switched between cutting and grinding without changing the tool. This study focuses on the effect of the angle $\theta$ between the fibre and the feed direction on the machined surface quality. CFRP was machined using $\theta$ = 0°, 45°, 90°, and 135°. In the cutting test, the average burr height was maximal at $\theta$ = 135°. By contrast, in the grinding test, the average burr height was minimal at $\theta$ = 135°. Therefore, the angle between the fibre and the cutting direction by the edge of cBN electroplated end-mill greatly influences the surface quality.

## Introduction

Carbon fibre reinforced plastic (CFRP) is widely used in various applications [1]. Although it is lighter than steel or aluminium, it possesses excellent mechanical properties including high specific strength, high specific elastic modulus, and high fatigue strength, as well as high electrical conductivity, good heat resistance, low thermal expansion, good chemical stability, self-lubricating properties, and high thermal conductivity, depending on the fibre matrix. Thus, the demand for CFRP has recently been increasing in various fields [2], as has the demand for a stacked material comprising CFRP and Ti-alloy. This has resulted in the need for high-efficiency machining methods, and accordingly, some new cutting tools and methods have been developed [3]. However, few studies have investigated the machining tool wear, the machined surface quality in term of burrs or uncut fibres, the degradation of CFRP mechanical properties with machining temperature, and the increase of non-machining time and machining cost. The main problem faced in these studies was the increase in tool temperature when machining a stacked material, as diamond tools have low thermal resistance and wear easily. Therefore, in this study, we developed a novel cubic boron nitride (cBN) electroplated end-mill that combines an end-mill with high machining efficiency and an electroplated tool which can be fabricated inexpensively compared to a diamond-coated end-mill [4]. This end-mill can be switched between cutting and grinding by changing the spindle rotation direction of the machining centre, without needing to change the tool. As CFRP is often used in combination with metals as stacked material, cBN abrasive with high thermal resistance and high hardness is used. In previous studies, we tried to determine the parameters for achieving high CFRP surface quality by varying the machining conditions and tool shape [5]. We also focused on the effect of the angle $\theta$ (= 15°, 30°, and 45°) between the fibre and the feed direction on the workpiece surface [6]. However, we failed to clarify the mechanism of burr formation and uncut fibres because the workpieces were twilled and were too complicated to observe. Thus, for simplicity in this study, workpieces made of unidirectional CFRP were machined at $\theta$ = 0°, 45°, 90°, and 135°.

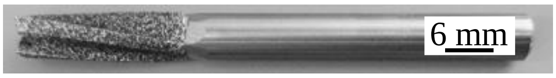



**Fig. 1** Developed cBN electroplated end-mill.

## Experimental method and set-up


**Fig. 2** Diamond-coated end-mill.


**Fig. 3** Diamond electroplated router.

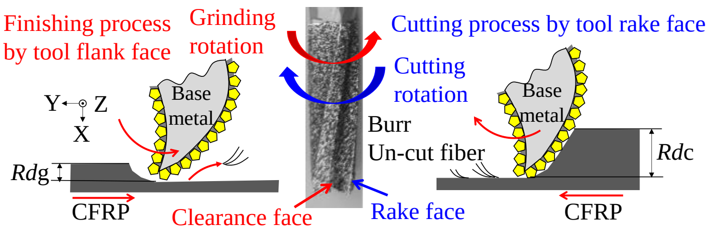
The developed cBN electroplated end-mill was used as the machining tool. It was compared with a diamond-coated end-mill and diamond electroplated router. Figures 1-3 show these respective tools. Tables 1, 2 show these tools' experimental conditions and specifications. The cBN electroplated end-mill was tested for cutting CFRP with clockwise rotation (Figure 4(a)) and for grinding CFRP with counterclockwise rotation (Figure 4(b)). The difference between cutting and grinding processes resides in the rake angle ($\alpha$) of the base metal. This angle is positive for cutting, and negative for grinding with $\alpha_{grinding} = \alpha_{cutting} - 90°$. Down-cut machining was performed with dry air as a coolant. Unidirectional CFRP workpieces were used. A prepreg P3252S comprising #2592 epoxy resin and T700SC carbon fibre (TOREY) was laminated in the same direction and moulded in an autoclave. The curing temperature was 130°C, and the glass transition temperature $Tg$ of the matrix resin was ~200°C. We machined the workpieces by varying $\theta$, as shown in Figure 5. The Acumill4000 machining tool (MORI SEIKI) with three-axis vertical machining centre was used. The CFRP temperature during machining was measured using the SC7000 infrared thermography camera (FLIR Systems, Inc.), as shown in Figure 6. Moreover, the burr height was measured using a microscope after the unidirectional CFRP was machined by 3 pathes (cutting length 55 mm/path).

**Table 1** Experimental condition and specifications of fabricated cBN electroplated end-mill (unidirectional CFRP).

| Machining process | Cutting | Grinding |
|---|---|---|
| Rotation direction | Clockwise | Counterclockwise |
| Cutting speed $V$ (m/min) | 100 | 150 |
| Feed per revolution $f$ (mm/rev) | 0.05, 0.1, 0.15 | 0.015 |
| Radial depth of cut $Rd_c$, $Rd_g$ (mm) | 1.0 | 0.1 |
| $\theta$ (°) | 0, 45, 90, 135 | |
| Coolant | Dry air | |
| Tool diameter $D$ (mm) | 6 | |
| Rake angle $\alpha$ (°) | 6 | |
| Helix angle $\beta$ (°) | 10 | |
| Clearance angle $\gamma$ (°) | 16 | |
| Number of cutting edges (teeth) | 4 | |
| Abrasive particles | #100 (Mean diameter = 147 µm, range = 127-167 µm) | |
| Material of base metal | Cemented carbide (K40) | |

**Table 2** Experimental condition and specifications of diamond-coated end-mill and diamond electroplated rooter (unidirectional CFRP).

| | | |
|---|---|---|
| Machining tool | Diamond-coated end-mill | Diamond electroplated rooter |
| Machining process | Cutting | Grinding |
| Rotation direction | Clockwise | Clockwise |
| Cutting speed *V* (m/min) | 100 | 150 |
| Feed per revolution *f* (mm/rev) | 0.15 | 0.015 |
| Radial depth of cut $Rd_c$ (mm) | 1.0 | 0.1 |
| $\theta$ (°) | 0, 45, 90, 135 | |
| Coolant | Dry air | |
| Tool diameter *D* (mm) | 6 | |
| Number of cutting edges (teeth) | 4 | 18 |
| Flute length *l* (mm) | 20 | #60 |
| Model number | SSDC4060 (Sumitomo Electric Industries) | ED-EM-6 (OSG) |




(a) grinding process with counterclockwise rotation (b) cutting process with clockwise rotation

**Fig. 4** Switching between machining processes by using a cBN electroplated end-mill.

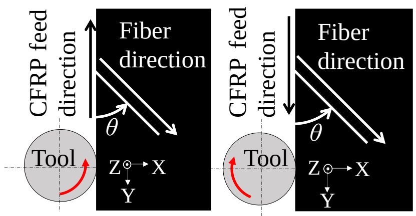



**Fig. 5** Definition of $\theta$.

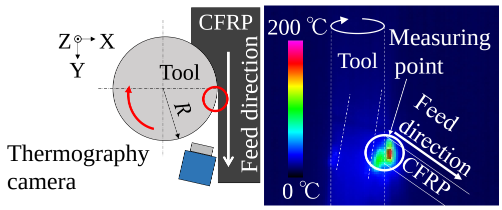



**Fig. 6** Schematic illustration of the measuring point and measurement example of CFRP temperature.


**Fig. 7** Cross section images after cutting tests with a cBN electroplated end-mill for $f$ = 0.15 mm/rev (unidirectional CFRP).

## Experimental results and discussion

### Observation of the machined surface.

**Cutting test with unidirectional CFRP.** Figures 7 and 8 show photographs of the surface machined using the cBN electroplated end-mill and the diamond-coated end-mill. In these figures, uncut fibres and burrs, which are short fibres, on the machined surface are indicated in yellow. In all cases of $\theta$ = 0° for any feed per revolution *f*, fibres bundles are stuck on the machined surface, unlike for other $\theta$

values. For $\theta$ = 90° and 135°, many uncut fibres were clearly seen. Uncut fibres for $\theta$ = 135° were more dense than those for $\theta$ = 90°. For $\theta$ = 45°, the machined surface hardly had any burrs or uncut fibres; therefore, the best surface was obtained in the cutting tests for $\theta$ = 45°.

**Grinding test with unidirectional CFRP.** Figure 9 and 10 show photographs of the surface machined using the cBN electroplated end-mill and diamond electroplated router. For $\theta$ = 0°, fibre bundles stuck on the surface, as in the cutting tests. For other $\theta$ values, few burrs or uncut fibres were seen, unlike in the cutting tests.

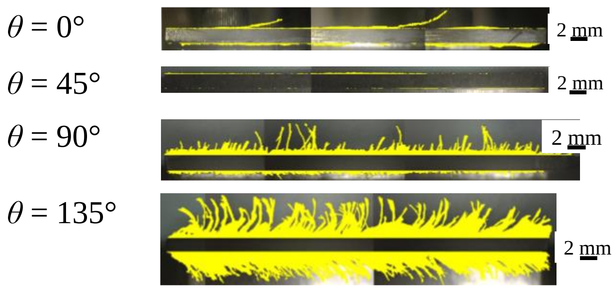



**Fig. 8** Cross-section images after cutting tests with a diamond-coated end-mill for $f$ = 0.15 mm/rev (unidirectional CFRP).

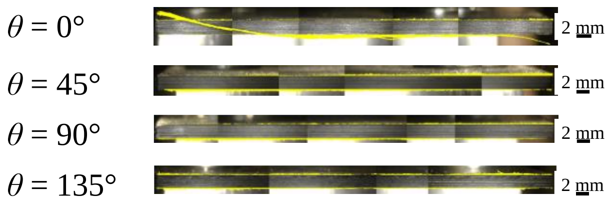



**Fig. 9** Cross-section images after grinding tests with a cBN electroplated end-mill for $f$ = 0.15 mm/rev (unidirectional CFRP).

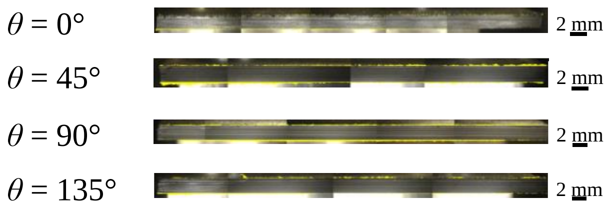



**Fig. 10** Cross-section images after grinding tests with a diamond electroplated router for $f$ = 0.15 mm/rev (unidirectional CFRP).

**Burr height.**

**Cutting test with unidirectional CFRP.** As shown in Figure 11, the average burr height is obtained by dividing the burr area indicated in yellow by the cutting length (55 mm) in the cross-section image. Figure 12 shows the relationship between the average burr height and $\theta$ in the cutting tests. For $\theta$ = 45°, 90°, and 135°, the higher the feed per revolution $f$, the larger was the average burr height, which increases with $\theta$. Figure 13 shows the model of the relationship between the edge of the cBN electroplated end-mill and the fibre direction of the unidirectonal CFRP in the cutting tests. In cutting tests using the cBN electroplated end-mill, the angle between the cut by the tool's edge and the feed direction is ~50° because the rake angle of the base metal is 6° and the clearance angle is 16°. For the condition $\theta$ = 45°, which had the smallest average burr height, the cutting direction is nearly the same as the fibre direction. Furthermore, for $\theta$ = 135° which had the largest average burr height, the cutting direction was almost vertical to the fibre direction. Therefore, the relationship between the fibre direction and the cutting direction by the edge of the cBN electroplated end-mill affected the surface quality. In cutting tests using the diamond-coated end-mill, the average burr height for $\theta$ = 90° and 135° for $f$ = 0.15 mm/rev was larger than the one obtained using the cBN electroplated end-mill. As shown in Figure 7, these uncut fibres were so large that the edges of the cBN electroplated end-mill and the cBN abrasive of the rake face both cut out the uncut fibres. Therefore, the cBN electroplated end-mill can prevent better the

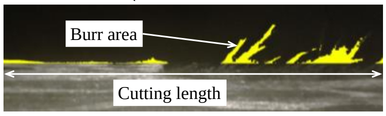



**Fig. 11** Method to measure the burr height.

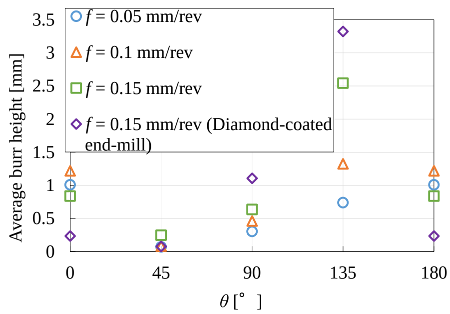



**Fig. 12** Relationship between average burr height and $\theta$ in cutting tests.

occurrence of uncut fibres compared to the diamond-coated end-mill, as it also acts as a cBN abrasive.

**Grinding test with unidirectional CFRP.** Figure 14 shows the relationship between the average burr height and $\theta$ in grinding tests. The diamond electroplated router produced smaller average burr heights than the cBN electroplated end-mill for all $\theta$ values. When using the cBN electroplated end-mill, the maximum average burr height was observed for $\theta$ = 0° (or 180°). Otherwise, the minimum and maximum heights were seen at $\theta$ = 135° and $\theta$ = 45°, respectively. This result is opposite to the one obtained in the cutting tests. In grinding tests using the cBN electroplated end-mill, the $\theta$values were kept the same as the one in cutting tests because the workpiece and tools used were the same for cutting and grinding in the clockwise and counterclockwise directions, respectively. Figure 15 shows the relationship between the edge and the fibre direction for grinding in the counterclockwise direction using the cBN electroplated end-mill. A comparison of Figure 15 with Figure 13 indicates an opposite relationship of the cutting direction between cutting and grinding processes. Let $\varphi$ be the angle between the fibre and the cutting direction by the edge of cBN in the cutting tests or the edge of the cBN abrasive in the grinding tests. At $\theta$ = 90°, $\varphi$ in the grinding test is the same as that in the cutting test. At $\theta$ = 45°, $\varphi$ in the grinding test becomes 135°, and at $\theta$ = 135°, $\varphi$ in the grinding test becomes 45°. This is why the average burr height showed opposite results between the cutting and grinding tests.

**CFRP maximum temperature**

**Cutting test with unidirectional CFRP.** Figure 16 shows the relationship between $\theta$ and the CFRP maximum machining temperature in the cutting test. If the CFRP temperature exceeds the glass transision temperature *Tg*, at which the glassy resin changes to an elastomer, the mechanical and thermal properties of the CFRP degrade and delamination occurs easily because of decreasing adhesion between layers. In this study, the CFRP had a *Tg* of 200℃, and no delamination was observed. As shown in Figure 16, the CFRP maximum temperature under the cBN electroplated end-mill did not depend on the feed per revolution *f*, except for $\theta$ = 45°, and was minimal for $\theta$ = 90°, as a large proportion of fibres were not cut on the edges. However, with the diamond-coated end-mill, the temperature was minimal for $\theta$ = 45°.

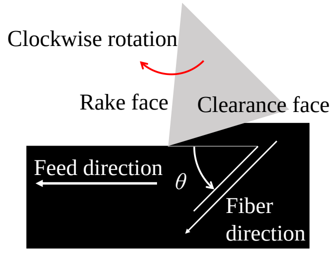



**Fig. 13** Relationship between the edge and the fibre direction for cutting tests in clockwise direction using a cBN electroplated end-mill.

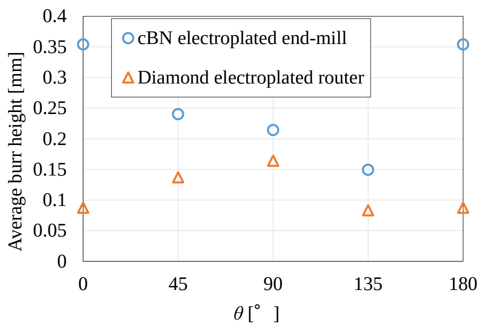



**Fig. 14** Relationship between the average burr height and $\theta$ in grinding tests.

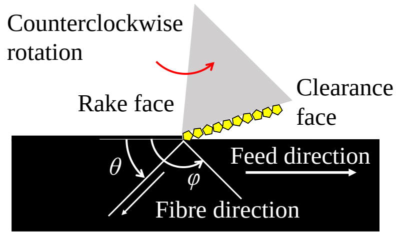



**Fig. 15** Relationship between the edge and the fibre direction for grinding tests in counterclockwise direction using a cBN electroplated end-mill.

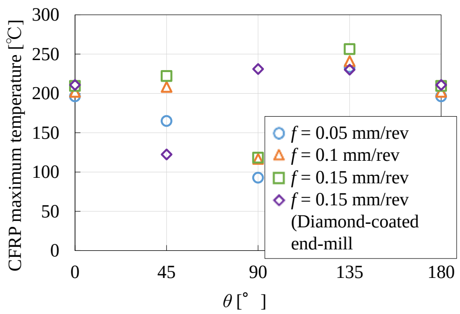



**Fig. 16** Relationship between $\theta$ and CFRP maximum temperature in cutting tests.

**Grinding test with unidirectional CFRP.** Figure 17 shows the relationship between $\theta$ and the CFRP maximum machining temperature in the grinding tests. The CFRP maximum temperature with the cBN elactroplated end-mill was around three times higher than with the diamond electroplated router for all the $\theta$ values. In the grinding test, the edges of an abrasive are considered to have the biggest effect on the machined surface because the radial depth of cut is only 0.1 mm. In tests using the diamond electroplated router, the diamond abrasive always affected the workpiece. However, in tests using the cBN electroplated end-mill, the cBN abrasive on the clearance face dose not affect the workpiece continually as it has four edges. Therefore, the cBN abrasive had to grind more of the workpiece than the diamond abrasive and had bigger load, thus making the machining temperature increase.

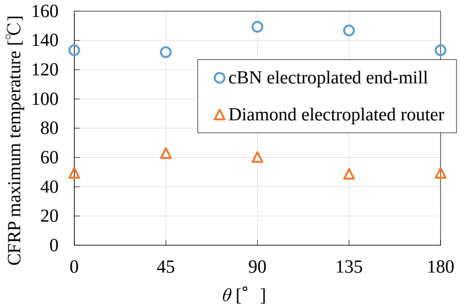



**Fig. 17** Relationship between $\theta$ and the CFRP maximum temperature in grinding tests.

## Summary


In this study, workpieces made of unidirectional CFRP were machined with $\theta$ = 0°, 45°, 90°, and 135° to determine the effect of the angle $\theta$ between the fibre and the feed direction on the workpiece surface. The following results were obtained.

1) A developed cubic boron nitride (cBN) electroplated end-mill, which can be switched between cutting and grinding without needing to change the tool, is found to be effective to machine CFRP.
2) The angle $\varphi$ between the fibre and the cutting direction has the largest effect on the machined surface under a constant cutting or grinding speed condition, and when it becomes around 45°, a better machined surface can be obtained.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