Research on the Durability of Tools and the Burrs of Workpiece When Milling T700 Carbon Fibre-reinforced Polymer Composites

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Abstract. This research aimed to analyse the life and the wear of the coated tools with a diamond thin film, the uncoated cemented carbide tools, and the quality of machined surface, respectively, when milling T700 carbon fibre-reinforced polymer (CFRP) composite using the optimal cutting parameters. The results indicate that (1) in the same cutting condition, the wear resistance of the coated tools with CVD diamond thin film is better, whose life is 7.5 times that of the uncoated cemented carbide tools. (2) The life of tools directly affects the quality of the machined surface. The size and density of burrs on the machined surface are proportional to the width of blade wear of tool when carbon fibre-reinforced polymer (CFRP) composite was machined. The coated tools with diamond thin film by Chemical vapour deposition (CVD) can effectively prevent the chemical wear and diffusion wear of tools, which will make the blade wear of tools slow and uniform. (3) In practice, based on the quality, efficiency and processing economy, the tools need to be regularly checked when the workpiece is cut to 5.4m, 40.5m length for uncoated tools and coated tools, respectively.

1. Introduction
The carbon fibre-reinforced polymer composite (CFRP) is an attractive class of engineering materials characterised by a series of superior performance, such as light quality, high specific strength, good wear resistance, high fatigue resistance and corrosion resistance, etc. [1, 2]. They have been widely utilised in many fields such as aerospace industry, aircraft manufacturing, atomic energy industry, automobile parts, sports equipment, agricultural machinery and medical equipment [3].

T700 carbon fibre-reinforced polymer composite is categorised to a kind of difficult-to-process materials [4-6]. The main challenges can be found in several aspects, specifically, it is quite likely to produce the stratification during further processing because of inherent layered graphite structure and relatively vulnerable shear stress and bending strength. [7-9].

The composites are anisotropically easy to split, thus, it is suggested that the direction of the reinforced fibres must be considered in processing. The high hardness and abrasion resistance of carbon fibres make the cutting tools worn rapidly. Moreover, it is necessary to employ cold compressed air during the process due to the poor thermal conductivity of composites.

At present, the studies on the carbon fibre-reinforced polymer composites (CFRP) remains at the beginning stage domestically as well as internationally. [8, 10]. Therefore, it is of great significance to find qualified tools suitable for machining the high strength carbon fibre-reinforced polymer composite (CFRP), determine the service life and wear mechanism and performance of tools, analyse the relationship between the blade wear of the tool and the quality of the machined parts. That is the
main reasons the researches emphasis on speeding up the practical engineering application of high strength carbon fibre-reinforced polymer composite (CFRP).

2. Experimental Materials and Procedure

2.1. Experimental Materials
The test materials are made of carbon fibre-reinforced polymer composites produced by Toray Company of Japan. The performance of the materials was shown in Table 1. The size of the sample is 330 mm × 333 mm × 1.2 mm (length × width × height).

| Reinforcement Material | Matrix Material | Laying Method /º | Volume Fraction of Fibre /% | Density /g.cm³ | Linear Density /mg/m | Elongation percentage /% | Longitudinal Tensile Strength /GPa | Transverse Tensile Strength /GPa |
|------------------------|-----------------|------------------|----------------------------|----------------|----------------------|--------------------------|-------------------------------|-------------------------------|
| T700                   | Epoxy Resin     | 90               | 60 ± 3                     | 1.80           | 800                  | 2.1                      | 4.9                           | 230                           |

2.2. Experimental Procedure and Detection Instruments
The test has experimented on the TAKAM TJ-700 CNC milling machine. The processing range of the machine is 800 mm × 550 mm (length × width). The rated power of the main motor is 7.5 kW, and the maximum speed of the spindle is 8000 rpm/min. The maximum speed of cutting feed (X, Y, Z axis) is 6000 mm/min.

The experimental result indicates two kinds of tools, which were uncoated cemented carbide tools and CVD diamond thin film coated carbide tools, were selected for the test, as shown in Figure 1. The uncoated cemented carbide tools were adopted the UBR4 series 4-blade flat end mills produced by Xiamen Jinlu Special Alloy Co., Ltd, and the diamond film coated carbide tools were adopted the 12-edge rhombic tools of the company EDW series. The parameters of the tools are shown in Table 2.

| Materials                | Diameter /mm | Number of teeth | Front angle (º) | Flank angle (º) | Helix angle (º) |
|--------------------------|--------------|-----------------|-----------------|-----------------|-----------------|
| Cemented carbide         | 8            | 4               | 7               | 15              | 30              |
| Diamond thin film        | 8            | 4               | 5               | 20              | 40              |

In order to ensure the success of the milling test, the special fixture designed by us was used for clamping the test material. The burr length of the machined surface was measured with a vernier calliper, and the macroscopic appearance of the burrs was filmed by a Fuji F505 EXR digital camera.

In order to reduce the number of tests, the cutting distance of this experiment is limited to 1.8 m, 3.6 m, 5.4 m, respectively. The test is expected to be finalised when the readings of uncoated tools reach the critical value of 4.5 m, 9 m, 13.5 m, 18 m, 22.5 m, 27 m, 31.5 m, 40.5 m, respectively. Followed by the measurement of the amount of flank wear of the tool and the size of the burrs of machined surface; and filming the macroscopic appearance of the burrs after processing. In order to ensure the accuracy of the test results, the method of averaging multi-blade measurement and multiple measurements are adopted.

Cooling method: dry cutting and using 301 high-power industrial grade vacuum cleaners produced by Zhejiang Yongkang Jeno Industry & Trade Co., Ltd. to cool the vacuum, as shown in Figure 2.

In order to obtain the readings of tool life value under the optimal cutting parameters, according to the proposed orthogonal test method before the subject, it would be necessary to combine with actual
production and the cutting test results obtained. The optimised cutting parameters are determined after the comparison: cutting speed $v = 5000$ rpm, feed rate $f = 250$ mm/min, depth of cut $a_p = 1$ mm.

The average wear amount of the flank of the tool $VB = 0.1$mm is set as the blunt standard of the tool, and the test is finished when the flank wear value is close to or equal to the blunt standard.

![Uncoated tool](image1)

![Coated tool with diamond](image2)

**Figure 1.** Test tools

**Figure 2.** Industrial vacuum cleaner

### 3. Analysis and Discussion of Test Results

#### 3.1. Variation of Flank Wear Width of Uncoated Tools

As shown in Figure 3, it is the flank wear width curve of the uncoated tool. It is clear from Figure 3 when the cutting distance is approaching to 5.4 m, the tool flank wear amount is close to the blunt standard value.

![Flank wear curve of uncoated tool](image3)

**Figure 3.** Flank wear curve of uncoated tool

#### 3.2. Variation of Flank Wear Width of Coated Tools

As shown in Figure 4, it is the flank wear width curve of the coated diamond film tool. It is clear from Figure 4 when the cutting distance is approaching to 40.5 m; the tool flank wear amount is close to the blunt standard value.

![Flank wear curve of coated tool](image4)

**Figure 4.** Flank wear curve of coated tool

#### 3.3. Tool Life Analysis

When milling T700 carbon fibre-reinforced polymer composites, flank wear is the main failure mode of the tool. The standard of the tool life is defined as the cutting distance of milling when the width of the flank wear band of the tool reaches the blunt threshold readings.

It can be seen from Figure 3 and Figure 4 that the uncoated tool is quickly worn, while the coated tool is slowly worn. Based on this fact it is believed that the uncoated tool experiences quick wear in
the beginning stage (the curve is steep), however, the coated tool exhibits good wear resistance during the beginning and normal stage (the curve is gentle). It is also clear that the milling length of the uncoated tool and the coated tool reached blunt standard at 5.4 m and 40.5 m respectively which can be calculated that the useful life of the coated tool is approximately 7.5 times longer than that of the uncoated tool.

From the test data above, when T700 carbon fibre-reinforced polymer composite was milled by the CVD diamond film coated tool, the curve is relatively flat, the change of wear amount is more stable, and the milling length is much larger than that of the uncoated cemented carbide tool. The reason is that the diamond coating of the tool can reduce the coefficient of friction between the tool and the workpiece, and it has a high thermal hardness to withstand a large amount of cutting heat generated by the machining. Since the surface of the uncoated cemented carbide tool has no thermal barrier, the huge cutting pressure between the tool and the surface of the workpiece will generate severe friction, and the temperature of the body of the tool will be instantaneously increased, which softens the material of the tool base, makes that the tool rapidly worn so that the life of the tool is greatly reduced.

The diamond coating material of the coated tool and the carbon fibre reinforcement in the composite are all carbon materials. Therefore, graphite acts as a solid lubricant when machining, which reduces the thermal stress of the friction, the adhesion of chips to the surface of the tool, prevents the formation of a built-up edge at the same time. The conclusion is that the tool life of CVD diamond film coated tools is much greater than that of uncoated cemented carbide milling tools when milling T700 carbon fibre-reinforce polymer composite.

3.4. Blade Wear Analysis
When T700 carbon fibre-reinforced polymer composites are milled with the uncoated and diamond coated carbide tools respectively, the blade wear profiles are shown in Figure 5.

It is obvious to witness from the figures that the wear resistance of the coated tool is better than that of the uncoated tool. Due to the periodic cutting in and out, the intermittent cutting is formed when machining. The cutting edge of the uncoated cemented carbide tool has a wide groove only after the milling length of 5.4 m, and the flank wear value of the tool has been close to blunt standard.

Compared with the uncoated cemented carbide tool, diamond coated tools show good wear resistance. When the milling length reaches 4.5 m, the flank wear amount is only 0.027 mm, and the cutting edge remains sharp. Simultaneously, when the milling length reaches 40.5 m, the flank wear value is just close to the blunt standard. At this time, the blunt region becomes larger, and most of the coating material is worn away, and greyish white matrix of the tool is exposed.

Based on the analysis of the wear mechanism, abrasive wear occurs in the uncoated and coated tools during cutting because the carbon fibres in the composite are hard points composed of graphite crystallites. With respect to uncoated cemented carbide tools, the high cutting temperatures will be produced due to friction between high hardness carbon fibres and tougher epoxy matrix materials and the tools during high-speed milling. The tool is accompanied by oxidative wear, diffusion wear and bonding, the number of wear increases sharply, and the blade tips or blades are easily broken to chipping. However, the CVD diamond coating material of tools is coated with a diamond film on the surface of the cemented carbide substrate of tools by chemical vapour deposition (CVD), which avoids the occurrence of chemical wear and diffusion wear in the cutting process. At the beginning stage of the cutting, the hard particles in the workpiece material continuously produce “micro-cut” to the surface of the tool coating, and the cutting edge of the tool will be manufactured to a similar “mechanical furrow” cutting mark. In the middle and late period of the cutting, as the enhancement of the reaction from abrasive particles and the rapid interaction between the workpiece and the tool, the powder of the diamond peeled off from the coating of the tool. Carbon fibre graphite microcrystalline powder from the composite plays a significant role in lubricating and polishing for the flank of the tool, so the wear of the flank face of the tool is relatively uniform and slow.
3.5. Influence of Tool Life on Surface Quality

The burr size of the machined surface by cutting the carbon fibre composites is shown in Figure 6 and Figure 7.

![Uncoated burr length curve](image1)

![Coated burr length curve](image2)

**Figure 6.** Burr length curve with uncoated tool  
**Figure 7.** Burr length curve with coated tool

It can be seen from Figure 7, when the milling length of the diamond coated tool reaches 40.5 m, at this time, the flank wear amount of the tool is close to the blunt standard value, the generated burrs on the machined surface are only 1.2 mm length, which is much shorter than that of the machined surface produced by cutting to the length of 1.8 m with the uncoated tools. Therefore, the use of the coated tool for processing can achieve a better surface quality of the workpiece.

The quality of the machined surface after cutting T700 carbon fibre composite is not only related to the length of the burrs generated, but also closely affect the density of the burrs. The macroscopic...
morphologies of the burr density produced by processing T700 carbon fibre composite are shown in Figure 8 and Figure 9.

It can be seen from Figure 8 and Figure 9, when machining with the diamond coated cemented carbide tool, the length of the burrs is tiny and the density of the burrs is sparse, and the quality of the machined surface processed in the whole life cycle of the tool is qualified and stable.

![Figure 8. Macroscopic appearance of burrs with uncoated tools at different milling lengths](image)

![Figure 9. Macroscopic appearance of burrs with coated tools at different milling lengths](image)

According to the variation curves of the burr length (Figure 6 and Figure 7) and the microstructures of the workpiece burrs (Figure 8 and Figure 9), it is obvious to conclude that the variation law of the burr length of the workpiece is positively correlated with the change curve of the tool life (Figure 3 and Figure 4). A gentle trend in the curve can be seen in the wear curves of the diamond coated tool and the curves of the burr length of the workpiece compared to the uncoated tool. With the milling length increases, the increases of width in the tool’s flank wear can be expected and the burrs tend to be coarse and dense, which is more obvious when machining with the uncoated tools.

The wear of coated tools is evenly and slowly consumed in processing because the diamond coating on the tool surface has a higher hardness than the T700 carbon fibre. Therefore, the burrs of the workpiece after processing are small, and the distance between the burrs is loose.

4. Conclusion
The T700 carbon fibre-reinforced polymer composite can be machined by milling, and the quality of the product is closely related to the type of machining tool selected.

When milling with CVD diamond film coated carbide tools, the burrs of the machined surface obtained are less than that of workpieces with the uncoated cemented carbide tools in the whole tool life cycle. At the same time, the burr density is lower, and the surface quality of the workpiece is superior.
CVD diamond film coated carbide tools can maintain long-term wear resistance during milling. Meanwhile, they have low wear and stability, and the tool’s durability can be as 7.5 times as that of uncoated carbide tools.

The main wear mechanism of diamond coated tools is abrasive wear caused by broken carbon fibre particles and resin matrix material for continuous wear and impact of the tool. The main damage forms of the tools are micro-cracking of the cutting edge and tip of the tools, flank coating wear and coating peeling caused by coating crack propagation.

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6. References
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