Comparative analyses on tool wear in helical milling of Ti-6Al-4V using diamond-coated tool and TiAlN-coated tool

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Abstract
This paper aims to establish the wear mechanisms of tungsten carbide (WC) tools coated with TiAlN and coated with diamond respectively when helical milling Ti-6Al-4V. During the helical milling experiments, cutting forces were measured using a dynamometer. In addition, a scanning electron microscope (SEM), a digital microscope and Energy-dispersive X-ray (EDX) were periodically used to measure the wear progression of tool surface and to analyze tool wear mechanisms. In the analysis of cutting force of two types of coating tools, cutting process of TiAlN-coated tool is more stable and cutting force of it is lower. TiAlN-coated tool showed a better cutting performance than diamond-coated tool. Tool wear mechanisms mainly include adhesive wear, oxidation wear, coating flaking and chipping and are combined effects of various wear forms. In view of flank wear analysis, diamond-coated tool has shorter life than TiAlN-coated tool, and it has undergone a relative severe wear.

Keywords: Tool wear, Ti-6Al-4V, Helical milling, Diamond-coated tool, TiAlN-coated tool

1. Introduction

In aircraft manufacturing, titanium alloys is becoming widely utilized due to excellent corrosion resistance, high strength to weight ratio and the ability to withstand high stress in service while reducing weight (Brinksmeier and Janssen, 2002). However, titanium alloys are ranked as difficult-to-machine material owing to low thermal conductivity, high chemical reactivity, low modulus of elasticity and serious work hardening. Cutting speed of processing titanium alloys is low and tool life is short (Ezugwu and Wang, 1997). Therefore, the problems that how to prolong tool life and how to improve processing efficiency are urgent and pressing. In order to improve productivity and reduce tool cost, it is desired to better understand the mechanisms for tool wear. Only in this way can these problems be addressed and overcome.

In the present work, tool wear mechanisms are investigated during helical milling of Ti-6Al-4V. The helical milling experiments were conducted with TiAlN-coated carbide tool and diamond-coated carbide tool at the same milling speed. The milling forces were measured for each hole using a dynamometer. The tool wear mechanisms acting on each tool were characterized through detection techniques such as scanning electron microscopy (SEM) and Energy-dispersive X-ray (EDX). The flank wear level was also obtained using SI-DUSB-8-1300k digital microscope. The relations between number of holes and tool wear values will be discussed, along with a summary of the tool wear mechanisms for TiAlN-coated carbide tool and diamond-coated carbide tool in helical milling of Ti-6Al-4V.

During machining process of titanium alloy, milling of titanium alloy is more difficult. The main problem is that tool is easily bonded with titanium at the cutting area due to strong chemical affinity and low thermal conductivity. Hence, this leads to cutter chipping and a reduction in tool life (Zhang, et al., 2008). In addition, the contact area
between the chip and the tool is shorter and its maximum cutting temperature is up to 1200 °C. These result in stress concentrations at the tool edge, high-temperature thermal effects, and ultimately accelerate tool wear (Ran and Zhang, 2012). Therefore, titanium alloys become typical difficult-to-machine materials, which inevitably put forward higher requirements on the tool material. Compared with the uncoated tool, diamond-coated tool has superior performance such as high hardness, low coefficient of friction, high wear resistance and high thermal conductivity. Precisely because of this, tool durability and tool life obtain substantial increase (Wei and Zhong, 2006). Further, manufacturing process of diamond coating is simple and cost of coating preparation is low, but the performance of diamond-coated tool is very close to natural diamond tool (Yin, et al., 2006). The coating preparation can get rid of the tool geometry constraints so that the preparation of complex surface coating is feasible (Li, et al., 2007). When the cutting speed is high, the high cutting temperature combined with low thermal conductivity and high chemical activity prompts titanium alloys easily to react with cemented carbide substrate and with the coating materials (Venugopal, et al., 2007). Therefore, it is recommended that titanium alloy machining should maintain in lower speed range (Li, et al., 2012).

When milling titanium alloy, tool failure forms is wear and tear. Morphology and mechanism of tool failure depend on the workpiece material, composition and microstructure of tool material, tool geometry parameters, cutting amount and cooling lubrication conditions (Li, et al., 2012). Compared with dry and flood coolant condition, the effect of application of minimum quantity lubrication (MQL) in high-speed helical milling of Ti-6Al-4V is feasible and obvious (Qin, et al., 2012). Also, the air jet toward the tool tip applied to the conventional wet machining was effective to extend tool life and to reduce tool wear (Toshiyuki, et al., 2011). With helical milling of titanium alloy going on, the tool wear increases and the tool cutting edges become blunt, which causes cutting force to increase. Hence, the cutting force measurement is necessary for answering tool wear mechanism undoubtedly. Cutting force in drilling of Ti-6Al-4V is studied by Shoichi TAMURA etc. with simulation based on a predictive model (OBIKAWA and KANI, 2012). According to milling experiments of Ti-6Al-4V, some particular types of micro-structured rake faces of a micro ball end mill can reduce the cutting forces effectively (TAMURA, et al., 2012). In the light of milling characteristics of titanium and tool wear test, Qin et al. developed dedicated tool geometry parameters for helical milling successfully, realized optimization of process parameters during helical milling of Ti-6Al-4V, and achieved desired results (Qin, et al., 2012)(Qin, et al., 2009).

Helical milling technology is different from drilling technology, which can generate holes for different diameters with one tool by changing offset value. It contains two kinds of movements, namely, rotation of the spindle and tool’s orbit rotation along pore diameter center (Fig. 1). There are great advantages compared with the drilling (Qin, et al., 2009). Firstly, helical milling process is intermittent cutting process and the chips produced are crescent-shaped chip breaker which is easy to remove, and also can effectively avoid chips from producing secondary injury on the machined surface; Secondly, Intermittent cutting process can reduce the accumulation of cutting heat and then reduce tool wear; Thirdly, the cutter diameter used for helical milling is smaller than the pore diameter. This is conducive to the direct role of the cooling medium to the cutting area and to improving the cooling efficiency; Furthermore, helical milling can reach accuracy requirements of aircraft assembly without assistance of other processes.

In our research group, we have researched tools with four kinds of coatings including uncoated, TiAIN coating, CrN coating, DLC coating, and learned that life of TiAIN-coated tool is longer than tools coated with other coatings through a large number of experiments under air cooling (Sun, 2012). CVD diamond coated tool can break the shackles
of complex geometry, coupled with its excellent characteristics, so comparison wear mechanism and tool life of diamond-coated tool with of TiAlN-coated tool is helpful to explore the feasibility of helical milling titanium alloy with diamond-coated tool.

2. Experimental procedures

2.1 Workpiece material

The titanium plate material used was Ti-6Al-4V with a thickness of 5 mm and a length of 250 mm and a width of 120 mm. Its chemical composition and main physical characteristics is shown in Table 1 and Table 2 respectively.

| Workpiece material | Chemical composition (mass %) |
|--------------------|-----------------------------|
|                    | Ti | Al | V | Fe | C | N | H | O |
| Ti-6Al-4V          | 89.405 | 6.0 | 4.2 | 0.16 | 0.02 | 0.03 | 0.005 | 0.18 |

| Density (kg/ m³) | Melting point (°C) | Elastic modulus (GPa) | Tensile strength (MPa) |
|------------------|-------------------|-----------------------|------------------------|
| 4428             | 1608              | 110                   | 932                    |

| Geometries of dedicated milling cutter. |
|----------------------------------------|
| Tool diameter (mm) | 6 | 6 |
| Number of flutes   | 4 | 4 |
| Rake angle (°)     | 12 | 12 |
| Helix angle (°)    | 40 | 40 |
| Overall length (mm) | 55 | 55 |
| Cutting edge length (mm) | 14 | 14 |
| Coating type       | Diamond | TiAlN |

2.2 Helical milling experiments

Two types of coating tools were selected for this investigation based on their widespread usage in industry: TiAlN-coated tool and diamond-coated tool. The diamond film was deposited on cemented carbide substrate by hot filament chemical vapor deposition (HFCVD), and was prepared by the BEIJING TIANDI ORIENT SUPERHARD MATRIALS CO., LTD. According to scratch tests in Fig.2 and Fig.3, binding strength between coating and substrate material of diamond coating is 3.915N (bonding strength is not good), 69.14N (bonding strength is proper) respectively for two different areas of diamond film. This illustrates that bonding strength is not even and varies widely. The part of poor bonding strength is likely to fall off in advance when it suffers from impact load. Both coating tools had a diameter of 6 mm and a rake angle of 12° and a helix angle of 40°. Also, substrate material of two tools used was cemented carbide. The surface roughness of TiAlN-coated tool and diamond-coated tool is 0.3496um and 0.3516um respectively. Table 3 summarizes the geometry dimensions of the tools used in the experiment. Fig.4 shows the real object photos of dedicated tool for helical milling.

Helical milling experiments were performed on a commercially available DMC75V linear 5-axis high speed machining center. And helical milling motion realized by motion compensation of machining center’s workbench. Ti-6Al-4V plate was mounted above the auxiliary aluminum plate, which had a groove and avoided the direct contact between Ti-6Al-4V plate and the dynamometer for safety of the dynamometer. Dynamometer was fixed on the workbench and auxiliary aluminum plate was located between the dynamometer and workbench. Ti-6Al-4V plate, auxiliary aluminum plate and the dynamometer were connected by four bolts so as to accurate measurement of cutting
force. The cutting force was transmitted from the dynamometer to signal amplifiers, then to an A/D board and recorded on personal computer using data acquisition software (Dynoware). The entire experimental step is shown in Fig. 5.

Fig. 2 Critical load of one area of diamond coating ($F_c=39.15\text{N}$).

Fig. 3 Critical load of the other area of diamond coating ($F_c=69.14\text{N}$).

Helical milling experiment conditions are summarized in Table 4. In order to investigate how different coatings affect tool wear and to eliminate the impact of other factors, the same spindle speed and orbit rotational speed and screw pitch and cooling condition were selected. Due to strong chemical affinity and low thermal conductivity of Ti-6Al-4V, its cutting speed should be not too high. And according to previous experiments of our research group \[10\]-\[14\], helical milling experimental parameters (spindle speed, orbit rotational speed and screw pitch) of TiAlN coating tool, namely, 3000rpm, 480mm/min, 0.15mm/rev, were optimum and suitable. Based on these cutting parameters, processing time needed to complete one hole is 105 seconds. Air cooling was used as a cooling method throughout the whole operation, which is conducive to increase chip evacuation and to reduce adhesion of titanium.

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alloy’s chip and to prolong tool life.

![Fig. 4 Dedicated milling cutters.](image1)

![Fig. 5 Schematics of experimental step for helical milling.](image2)

Table 4  Experiment conditions of helical milling.

|                     | TiAIN coating tool | Diamond coating tool |
|---------------------|--------------------|----------------------|
| Spindle speed (rpm) | 3000               | 3000                 |
| Orbit rotational speed (mm/min) | 480 | 480 |
| Screw pitch (mm/rev)   | 0.15               | 0.15                 |
| Cooling condition       | Air cooling        | Air cooling          |

2.3 Analysis on wear mechanism

Tool wear has been investigated typically using a number of instruments and techniques that include a SI-DUSB-8-1300k digital microscope, SEM, and Energy-dispersive X-ray (EDX). SEM is used to observe the various forms of tool wear. Digital microscope enables us to examine the tool wear morphology after completing a specified number of holes on Ti-6Al-4V plate. EDX aims to identify tool surface’s chemical elements for analyzing tool wear mechanism. Besides, the measure of cutting force is carried out by a piezo-electric dynamometer (Kister 9257B).

3. Results and discussion

3.1 Milling forces

From the Fig.6, we can see that cutting force changes over the number of holes. Given that tool coatings are two different film materials (TiAIN film and diamond film), so the cutting forces are different.
When conducting helical milling of the first hole, the maximum axial component ($F_{z,\text{max}}$) of cutting force of diamond-coated tool increased dramatically, and $F_x$ and $F_y$ of it are all higher than that of TiAlN-coated tool (Fig. 8). In contrast, cutting force of TiAlN-coated tool is relatively stable. The reason for this tide is that diamond coating tool is in the initial wear stage. In the period, diamond grains is larger and flank face coating is rough and uneven since there is no surface treatment for diamond coating, which lead to smaller contact area between flank face and workpiece surface and then lead to increases of compressive stress. Consequently, cutting force of diamond-coated tool is higher than that of TiAlN-coated tool when milling the first hole.

As showed in Fig. 7, relative value of maximum axial cutting force was calculated by using Eq. (1).

$$\text{Relative value} = \frac{F_{z,\text{max, diamond-coated}} - F_{z,\text{max, TiAlN-coated}}}{F_{z,\text{max, TiAlN-coated}}} \times 100\%$$  (1)

It is seen from Fig. 7 that maximum axial cutting force of diamond-coated tool is higher than that of TiAlN-coated tool except merely three holes. The results agree well with the following experimental study results which show more severe wear of diamond-coated tool. Based on uneven bonding strength between coating and substrate material, widespread use of diamond-coated tool is limited.

In the steady wear stage, Fig. 6 illustrated that $F_{z,\text{max}}$ value of diamond-coated tool located between 200 N and 300 N, and that of TiAlN-coated tool ranged from 100 N to 200 N. However, it must be noted that its average value ($F_{x,\text{ave}}, F_{y,\text{ave}}, F_{z,\text{ave}}$) was close to that of TiAlN-coated tool, as depicted in Fig. 9. Last but not least, $F_{z,\text{max}}$ value of diamond-coated tool fluctuated obviously, while that of TiAlN-coated tool was relatively stable, as can be seen in Fig. 6. The reason for these phenomena was probably due to uneven bonding strength between diamond coating and tool substrate material. In fact, part of diamond coating began to fall off after finishing the third hole. In spite of that, the
tool failure did not occur, and the tool still possesses a long service life. In the process of milling titanium alloy, bottom cutting edges and peripheral cutting edges were all involved in cutting workpiece materials, and peripheral cutting edges alleviated the pressure of bottom cutting edges, so that bottom cutting edges did not need to withstand excessive cutting force. In addition, advantages of diamond-coated tool, such as high hardness, wear resistance, low friction coefficient, are also an important reason for no premature failure. Hence, shedding of part of diamond coating on bottom cutting edges had no great effect on its overall cutting performance. But, its cutting process was not steady, which manifested that fluctuation of $F_{\text{ave}}$ as apparent, but fluctuation of average cutting force was not obvious. Unlike helical milling process, drill suffered greater drilling force since peripheral cutting edge was not involved in cutting workpiece materials and drilling force focused on the bottom edge of drill. Therefore, even if small defects of the tool also led to tool failure and destruction. Of course, there is no doubt that shedding diamond coating promoted the shedding of its surrounding coating. Seen from relatively steady cutting force of TiAlN-coated tool, with respect to helical milling of Ti-6Al-4V material, TiAlN-coated tool showed a better cutting performance than diamond-coated tool. In summary, for diamond-coated tool, bonding strength between diamond coating and matrix material is a key problem.

![Force signal profiles](image)

**Fig. 8** Cutting force signal profiles with different coating tools.

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3.2 Tools wear mechanism

3.2.1 Adhesive wear

The reasons for the tool material locally having anisotropic properties are probably that structure of the tool material is not uniform, there are many defects and cracks, distribution of internal stress and chemical composition is uneven and so on. Also, there are big differences in micro-hardness of various parts of the tool. Therefore, at the weak link of the tool material, wear occurs due to adhesion.

According to the element analysis results by EDX, flank faces of both TiAlN-coated tool and diamond-coated tool adhere with some Ti-6Al-4V materials (Fig. 10). Hence, the tools have occurred adhesion abrasion.

![Fig. 10 SEM micrographs and EDX results of adhesive wear of tools.](image)

| Element | Mass(%) | Atom(%) |
|---------|---------|---------|
| Al      | 4.55    | 6.85    |
| Ti      | 93.00   | 91.02   |
| V       | 2.45    | 2.13    |
| Total   | 100.00  | 100.00  |

Fig. 9 Average cutting force in steady stage.
Table 6  Elemental analysis results by EDX in Fig. 10 (N).

| Element | Mass(%) | Atom(%) |
|---------|---------|---------|
| Al      | 3.85    | 6.65    |
| Ti      | 92.85   | 90.33   |
| V       | 3.30    | 3.02    |
| Total   | 100.00  | 100.00  |

Because of strong adhesion, high chemical activity and strong affinity of Ti-6Al-4V materials, flank faces are easy to adhere with some Ti-6Al-4V materials and then become adhesive layers by accumulation when they are in high temperature and pressure conditions. In the process of mechanical impact, adhesive layers fall off from the surface of the tool and then tear off particles of part tool material inevitably, which causes the tool wear.

3.2.2 Oxidative wear

In the high-temperature environment, some elements and substances in tool material (such as titanium, aluminum, cobalt, tungsten carbide and titanium carbide) react with oxygen in the air chemically, forming a layer of oxide film (its ingredient is mainly TiO₂, Al₂O₃, CoO, Co₃O₄, WO₃, TiO₂ etc.) which has poor bonding strength and low hardness. This easily leads to some phenomena that carbide particles in tool material are cline to be taken away by chips or to be destroyed by friction, which causes continual loss of surface material, resulting in oxidative wear of tools. According to the analysis of Fig. 11, Table 7 and Table 8, atomic percent of oxygen atom in the measuring areas are high (TiAlN-coated tool is 17.82% and diamond-coated tool is 19.65%), which suggests that both TiAlN-coated tool and diamond-coated tool have occurred oxidative wear.

Table 7  Elemental analysis results by EDX in Fig. 11 (P).

| Element | Mass(%) | Atom(%) |
|---------|---------|---------|
| C       | 11.00   | 29.76   |
| O       | 9.67    | 19.65   |
| Al      | 2.96    | 3.56    |
| Ti      | 63.88   | 43.36   |
| V       | 2.49    | 1.59    |
| Co      | 0.82    | 0.45    |
| W       | 9.18    | 1.62    |
| Total   | 100.00  | 100.00  |

Fig. 11 SEM micrographs and EDX results of oxidative wear.
Table 8  Elemental analysis results by EDX in Fig. 11 (Q).

| Element | Mass(%) | Atom(%) |
|---------|---------|---------|
| C       | 10.27   | 20.24   |
| N       | 10.78   | 18.22   |
| O       | 12.05   | 17.82   |
| Al      | 24.54   | 21.52   |
| Si      | 3.68    | 3.10    |
| Ti      | 38.68   | 19.11   |
| Total   | 100.00  | 100.00  |

3.2.3 Coating flaking

Coefficient of linear expansion of surface coating materials on coated carbide blade varies widely from that of matrix material, which results in residual stress on the surface of blade and then brings about coating flaking on rake face or flank face of tools. Besides, in helical milling process, stresses caused by cyclical mechanical load and thermal load also lead to coating breaking and shedding. When the coating peeled off, the cutter matrix material exposed out, which accelerated tool wear. As a result, once the coating peeled off in a large area, the protective effect of the coating on the substrate exists no longer, and then the tool failure will happen soon. As can be seen from Figure 12, the two coatings peeled off and diamond-coated’s flaking was even more serious after finishing the last hole owing to its poor bonding strength.

Fig. 12 SEM micrographs of coating flaking of TiAlN-coated tool and diamond-coated tool.

3.2.4 Chipping

Figure 13 shows the electron micrograph of TiAlN-coated tool during milling the ninth hole, the electron micrograph of diamond-coated tool when milling the sixty-third hole, and the electron micrograph of diamond-coated tool when generating the sixth hole respectively. It is obvious that chipping is one of the main forms of tool breakage. Seen by the principle of metal cutting, it is clearly observed that the reasons for chipping are that the microstructure, hardness and margin of the workpiece material are not uniform or process system vibrates due to less rigid or helical
milling is an intermittent cutting way or sharpening quality is poor and so on. For micrographs of the ninth hole and the sixth hole, the reasons for chipping are probably due to above statement. But, for micrograph of the sixty-third hole, it is mechanical fatigue and thermal fatigue that give rise to tool chipping. When the tool chipping occurs, the tool machinability will be lost partly, but still can continue to work.

![Fig. 14 Wear mechanism of diamond-coated tool.](image)

| Table 9  | Elemental analysis results by EDX in Fig. 14 (A). |
|----------|-------------------------------------------------|
| Element  | Mass (%) | Atom (%) |
| C        | 42.36    | 60.83    |
| O        | 5.69     | 6.13     |
| Al       | 51.34    | 32.82    |
| Ti       | 0.61     | 0.22     |
| Total    | 100.00   | 100.00   |

| Table 10 | Elemental analysis results by EDX in Fig. 14 (B). |
|----------|-------------------------------------------------|
| Element  | Mass (%) | Atom (%) |
| C        | 80.95    | 87.13    |
| O        | 14.09    | 11.39    |
| Al       | 0.68     | 0.33     |
| Ti       | 4.27     | 1.15     |
| Total    | 100.00   | 100.00   |

| Table 11 | Elemental analysis results by EDX in Fig. 14 (C). |
|----------|-------------------------------------------------|
| Element  | Mass (%) | Atom (%) |
| C        | 12.32    | 41.43    |
| O        | 7.04     | 17.78    |
| Al       | 2.24     | 3.35     |
| Ti       | 27.54    | 23.23    |
| V        | 1.23     | 0.98     |
| Co       | 4.99     | 3.42     |
| Total    | 100.00   | 100.00   |
3.2.5 Combined effects of all kinds of wear forms

Instead of working on tool wear by single wear form, tool wear is the result of combined effects of various wear forms. As mentioned above, helical milling process is an intermittent cutting way. Under such circumstance, tool withstood impact and thermal loads, so that the coating was shaken and softened. When combination intensity limit of between the coating and the substrate is reached, the coating flaking occurred. It is likely that this led to subsequent adhesive wear. Fig. 14 and Fig. 15 detail different wear forms in each region of tool surface. According to this, tool wear mechanism was consisted of combined effects of all kinds of tool wear forms. From Fig. 14 and Table 9, Table 10, Table 11, it was found that region (A) revealed that diamond-coated tool took place oxidation wear and adhesive wear, and region (B) showed its oxidation wear, adhesive wear, and region (C) displayed its oxidation wear, adhesive wear and coating flaking. It can be observed from Fig. 15, Table 12, Table 13 that region (D) exhibited adhesive wear, coating flaking of TiAlN-coated tool and region (E) illustrated its oxidation wear, coating flaking. In summary, tool wear is a complex process, and is formed from combined effects.

![Fig. 15 Wear mechanism of TiAlN-coated tool.](image)

| Element | Mass (%) | Atom (%) |
|---------|----------|----------|
| C       | 10.48    | 49.82    |
| Al      | 1.18     | 2.50     |
| Ti      | 14.30    | 19.43    |
| V       | 1.43     | 1.60     |
| Co      | 7.15     | 6.93     |
| W       | 63.46    | 19.71    |
| Total   | 100.00   | 100.00   |

| Element | Mass (%) | Atom (%) |
|---------|----------|----------|
| C       | 18.58    | 32.60    |
| N       | 18.00    | 27.07    |
| O       | 8.29     | 10.92    |
| Al      | 18.52    | 14.47    |
| Ti      | 33.02    | 14.53    |
| W       | 3.59     | 0.41     |
| Total   | 100.00   | 100.00   |
3.3 Tool life analysis

Tool wear process is divided into three stages: initial wear stage, steady wear stage, rapid wear stage. Select VB=0.2mm as a blunt standard in this paper. Figure 16 presents that there are some differences between diamond-coated tool and TiAlN-coated tool in the aspect of the level of tool flank wear. On the one hand, in the light of the uneven bonding strength of diamond coating compared with that of TiAlN coating and strong adhesion of titanium alloy, diamond-coated tool obtains a little shorter life than TiAlN-coated tool, which is exhibited by producing more holes, namely, 70 holes compared to 88 holes of TiAlN-coated tool. On the other hand, the slope in initial wear stage of diamond-coated tool is greater than that of TiAlN-coated tool which dues to lacking of polishing and grinding treatment to diamond coating prepared freshly. Besides, the value of flank face wear of diamond-coated tool is higher than that of TiAlN-coated tool, which has inherent consistency with the tendency of maximum axial cutting force in Fig. 6. The reason for this trend is that mechanical load and thermal load make the diamond coating easy to fall off from cemented carbide substrate in intermittent cutting process. Finally, it is evident that the whole wear process (including initial wear, steady wear and rapid wear) of diamond-coated tool is less even and smooth than that of TiAlN-coated tool. This mirrors indirectly uneven bonding strength of diamond coating.

4. Conclusion

Wear mechanism of both TiAlN-coated tool and diamond-coated tool in helical milling of Ti-6Al-4V was evaluated in this paper. Based on the results of the present experimental investigation, the following conclusions have been reached.

(1) Cutting force’s variation trend can be able to reflect the extent of tool wear to some extent. In the analysis of cutting force of the two kinds of coating tools, cutting process of TiAlN-coated tool is more stable and its maximum axial cutting force is lower. Therefore, TiAlN-coated tool showed a better cutting performance than diamond-coated tool.

(2) It is better to improve bonding strength between film and substrate in order to gain longer life for diamond-coated tool. However, due to helical milling, diamond-coated tool with poor bonding strength still met the requirements of hole-making and had obtained a longer service life yet.

(3) Wear forms of both diamond-coated tool and TiAlN-coated tool mainly include adhesive wear, oxidation wear, coating flaking and chipping.

(4) Based on tool wear forms mentioned above, tool wear is the result of combined effects of various wear forms.

(5) In the light of flank wear analysis, diamond-coated tool gets shorter life than TiAlN-coated tool, and it has undergone a relative severe wear, which is consistent with the trend of maximum axial cutting forces.
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References

Brinksmeier, E., and Janssen, R., Drilling of multi-layer composite materials consisting of carbon fiber reinforced plastics (CFRP), titanium and aluminum alloys, CIRP Annals-Manufacturing Technology, Vol.51 (2002), pp.89–90.

Ezugwu, E. O., and Wang, Z. M., Titanium alloys and their machinability-A review, Journal of Materials Processing Technology, Vol. 68, No. 3 (1997), pp.263–274.

Li, A., Zhao, J., Luo, H., and Pei, Z., Wear mechanisms of coated carbide tools in high-speed, dry milling of titanium alloy, Tribology, Vol.32, No.1 (2012), pp.40–46.

Li, W., Jian, X., and Ding, Y., Study on fabrication technology and cutting test for complex-geometry diamond-coated tools, Chinese Journal of construction Machinery, Vol.5, No.1 (2007), pp.91–94.

OBIKAWA, T., FUNAI, K., and KAMATA, Y., Air jet assisted machining of titanium alloy, Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol.5, No.2 (2011), pp.139–149.

OBIKAWA, T., and KANI, B., Micro ball end milling of titanium alloy using a tool with a microstructured rake face, Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol.6, No.7 (2012), pp.1121–1131.

Qin, X., Chen, S., Liu, W., Ni, W., and Liu, Y., Development and application of hole helical milling technology in aviation manufacturing assembly industry, Aeronautical Manufacturing Technology, Vol.6 (2009), pp.58–60.

Qin, X., Gui, L., et al., Feasibility study on the minimum quantity lubrication in high-speed helical milling of Ti-6Al-4V, Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol.6, No.7 (2012), pp.1222–1233.

Ran, Q., and Zhang, Y., The milling technology of titanium alloy among aerospace products, Metal Working, Vol.3 (2012), pp.32–34.

Sun, X., Optimization and Experimental Research of Helical Milling Special Tool for CFRP/Titanium Alloy [D]. Tianjin: Tianjin University, 2012 (in Chinese).

TAMURA, S., MATSUMURA, T., and ARRAZOLA, P. J., Cutting Force Prediction in Drilling of Titanium Alloy, Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol.6, No.6 (2012), pp.753–763.

Venugopal, K. A., Paul, S., and Chattopadhyay, A. B., Tool wear in cryogenic turning of Ti-6Al-4V alloy. Cryogenics, Vol.47, No.1 (2007), pp.12–18.

Wei, S., and Zhong, Q., Research on cutting performance of diamond coated tool, Metal Processing Technology, Vol.4 (2006), pp.91–92.

Yin, H., Ding, Z., and Yang, H., The experimental research on the cutting properties of CVD film diamond coated tools, Metal Processing Technology, Vol.5 (2006), pp.24–25.

Zhang, P., Chari, N., Pei, Z., and Treadwell, C., Mechanical drilling processes for titanium alloys: a literature review, Machining Science and Technology, Vol.12 (2008), pp.417–444.