Experimental Study on the Influence of Tool Wear on the Cutting Process of Ti6Al4V

Qimeng Liu, Jinkai Xu and Huadong Yu

Ministry of Education Key Laboratory for Cross-Scale Micro and Nano Manufacturing, Changchun University of Science and Technology, Changchun 130022, China.

Correspondence to: Huadong Yu, Ph.d.
*Corresponding Author Email: yuhuadong@cust.edu.cn

Abstract. The tool wear is a big problem when machining titanium alloy. If the tool wear law is not mastered well, the machining quality will not be guaranteed. In this paper, the theoretical model of the tool is established, which can understand the spatial dimension model of the tool. At the same time, the tool wear experiment of the most commonly used tool for titanium alloy machining in the manufacturing industry is carried out, and the influence of the tool cutting wear on the cutting process is studied. The experimental analysis shows that the tool produces the chip extrusion stripe when it is worn in the initial stage and normal stage, which is perpendicular to the chip in the outflow direction, the fringe protrusions are parallel, and the contact surface of the chips is relatively flat. When the tool reaches the stage of severe wear, the protrusion stripes perpendicular to the outflow direction of the chips are fluffy, and the stripes are twisted. With the continuous cutting wear time of the tool becoming longer, the cutting force, the residual stress of the machined surface layer and the cutting temperature obtained in each stage gradually increase; with the tool reaching the stage of severe wear, the protrusion stripes are fluffy, and the stripes are twisted. The tool wear time gradually increases, and the cutting surface roughness obtained by continuous tool wear decreases first and then increases; the surface quality of the tool in the initial wear stage is relatively obvious and the edge burr is large, while in the normal wear stage, the surface quality of the tool is gradually gentle, but when the tool reaches the severe wear stage, the surface quality of the tool begins to be processed Sharp drop and thick edge burr.

1. Introduction

Titanium alloy has high specific strength, high temperature resistance, corrosion resistance and other excellent properties. It has been widely used in engine case and other key bearing components, and has broad application prospects in aerospace and other important fields. But its thermal conductivity is low, its chemical property is active, its cold and hard phenomenon is serious, its deformation coefficient is small, it is easy to aggravate the tool wear when cutting, so it is a typical difficult to machine material. In cutting process, cutting force, cutting heat and chip formation process have different effects on the surface of parts, and the micro morphology of parts has an important influence on its service performance. Therefore, it is of great significance to study the design of end mills and the prediction of tool wear for the development of mechanical industry [1-4].

In recent years, many scientists have done a lot of research on the establishment of tool model and the influence of tool wear on machining characteristics. Professor Zhao Jun established an accurate model of milling cutter by determining the cutting edge line and spiral groove end section, which provided a theoretical basis for the design of milling cutter [5]. According to its invariance, Professor
Sun Xiuyuan uses the natural axis coordinate system to model the attitude of the grinding wheel, and obtains a general normal vector equation of the grinding wheel end face and the central coordinate equation of the grinding wheel end face [6]. J BONNYA studied the optimal processing parameters for each material to improve the service life of cutting tools in milling difficult materials [7]. M NOUARI studied the tool wear when milling titanium alloy materials. It was observed in the study that when the cutting speed reaches a certain value, the tool will appear edge collapse, boundary wear, diffusion wear and bond wear [8]. Professor Dong Guojun has carried out molecular dynamics simulation and Experimental Research on tool wear mechanism in cutting aluminum alloy, and studied tool wear mechanism according to the change of chemical composition of tool tip [9]. The tool wear is a big problem when the tool is machining titanium alloy. The cutting edge of the tool is a sharpening process in the initial wear stage. The machining of each cutting edge of the tool can not play the role of the best coupling machining, which has a direct impact on the machining of the elastic deformation zone. The surface machined by titanium alloy in this state is not the best machining stage. In this paper, further in-depth study is carried out for different wear degrees of cutting tools to study the influence of different tool wear on the machining process of Ti6Al4V material, and the wear stage that can obtain the best surface quality and machining accuracy is obtained through experiments.

Therefore, in this paper, the theoretical model of the tool is established first, which can understand the spatial dimension model of the tool. Secondly, the tool wear experiment is analyzed. Finally, through the end milling experiment of Ti6Al4V material, the influence of milling parameters on the tool wear life is analyzed, and the influence of the tool continuous wear on the cutting process at different time states is studied, which provides the practical basis for the machining of Ti6Al4V parts.

2. Analysis of Tool Wear Mechanism

According to the characteristics of tool wear, it can be divided into three areas: tip wear area, uniform wear area and close to the wear area to be processed. The wear area of milling cutter is shown in Fig. 4. The formation of the wear area at the tool tip is due to the high temperature and poor heat dissipation conditions; the formation near the wear area is caused by the hardening layer formed on the machined surface or surface oxidation, which can also be called boundary wear; the wear of uniform wear area is relatively uniform.

Figure 1. Model of milling cutter and wear of tool tip

2.1. Experimental Analysis of Tool Wear Mechanism

2.1.1. Design of tool wear experiment scheme.
A force platform and a temperature measuring instrument are installed on the work platform of the machine tool. Besides, an X-ray residual stress measuring instrument is available to measure the residual stress of the processed sample, and a scanning electron microscope is employed to present the morphological structures of chip and surface of the processed sample. A surface roughness meter is used to measure surface roughness of the treated sample. The experimental platform is shown in Fig. 2.
In this paper, the experimental milling method is down milling and dry cutting, and the machining step is 50% of the cutter diameter, a TiSiN-coated end milling cutter with diameter of 6mm, 4 edge, and helix angle of 45° was selected for the experiment, as shown in Table 1.

![Figure 2. Experimental platform.](image)

**Table 1. Tool wear test plan**

| Tool type | Diameter: 6mm, 4 edge, a front angle of 30°, a back angle of 14° and a helix angle of 45°, surface coating: TiSiN carbide milling cutter. | Property parameters of Ti6Al4V |
|-----------|---------------------------------------------------------------------------------------------------------------------------------|--------------------------------|
| Spindle speed (r/min) | 4000, 6000, 8000, 10000 | Density (kg/m³) 4440 |
| Feed rate (mm/min) | 800 | Modulus of elasticity (GPa) 640 |
| Cutting depth (μm) | 50 | Hardness (HV) 340.6 |
| Steps (%) | Diameter×50% | Poisson's ratio 0.33 |
| Milling method | Down milling | Yield strength (GPa) 835 |
| Tool wear time (min) | 10, 20, 30, 40, 50 | Thermal conductivity (W/mK) 6.8 |
|                      |                        | Density (kg/m³) 4440 |

2.1.2. Design of tool wear experiment scheme.

The wear process of milling cutter is generally divided into three stages: initial wear, normal wear and severe wear. The initial wear is mainly determined by the manufacturing level of the cutting edge. After rapid wear, the cutting edge is passivated by wear to make it transition to the normal wear stage. The surface quality of normal wear stage is stable, and the cutting surface quality is the best. When the tool is worn for a certain period of time, under the coupling effect of mechanical vibration, temperature, material hardening and other factors, the tool wear increases sharply, the coupling temperature in the cutting area increases sharply, and the cutting will appear melting or even sticking phenomenon. After cutting to the limit, even the phenomenon of cutting edge collapse occurs, and the cutting index cannot be achieved.

In order to further analyze the cause of tool wear, the energy spectrum analysis of tool front and rear tool surface is carried out by using scanning electron microscope, and the tool wear mechanism is analyzed by detecting the element composition change in specific area. Figure 3 shows the wear

![Figure 3. Wear mechanism.](image)
morphology and EDS spectrum analysis of the front and rear cutting surfaces of the tool. Through the comparative analysis of the elements at a and B of the rake face, it is obvious that a certain amount of tungsten, cobalt, nitrogen and oxygen are found at the tool tip A. At the same time, the content of tungsten, cobalt and nitrogen in the tool substrate increases, which indicates that the matrix elements are leaked out of the tool coating due to wear, and a certain amount of oxygen element is found at the tool tip a, which can prove that Ti6Al4V is in good condition. In the milling process, oxidation wear occurs in the wear area of the rake face. However, Part B is far away from the tool tip, where the content of energy spectrum elements is the tool matrix element, indicating that there is no tool wear. In the area where the distance between the rake face and the cutting edge is very narrow, it is found that the tool rake face is bonded. Therefore, the bond wear occurs in the wear area of the rake face. Through the comparative analysis of the elements at C and D on the back face, it is obvious that a certain amount of titanium is found at the tool tip C, while the content of nitrogen and silicon in the tool base decreases. It can be proved that diffusion wear occurs in the flank wear area during Ti6Al4V milling. However, D is far away from the tool tip, where the energy spectrum element content is the tool matrix element, indicating that there is no wear.

**Figure 3. Wear morphology and EDS energy spectrum analysis of cutting tool**
In Fig. 3, a certain amount of titanium and oxygen elements are found on the surface of the fresh notch worn by the tool. In the area where the front face is very narrow from the cutting edge, it is found that the back face of the tool is bonded. At the same time, the content of tungsten and cobalt in the matrix increases due to the wear of the tool coating, and a certain amount of titanium is found to increase on the cutting surface. It can be proved that during the milling process of Ti6Al4V, the tool has oxidation wear, adhesive wear and diffusion wear. In conclusion, the wear mechanism of cemented carbide tool milling Ti6Al4V mainly includes oxidation wear, adhesion wear and diffusion wear.

Cutting parameters (n=4000 r/min, F=800 mm/min, ap=50 μm) are commonly used in end milling. Fig. 4 shows the change rule of the relationship between the maximum wear of the cutting face and the milling time at each time when the tool is machining Ti6Al4V under this set of parameters.

As can be seen from Fig. 4, in the milling process of Ti6Al4V, the tool wear rate changes from fast to slow and then to fast. According to the theory of metal cutting, the process can be divided into three stages: initial wear stage, normal wear stage and severe wear stage.

![Figure 4. The relationship between the maximum wear of the front and back face of the tool and the milling time in each time of machining Ti6Al4V](image)

The wear diagram of the tool at each time is shown in Fig. 5.

![Figure 5. Tool wear map at each time](image)

(a) Tool wear 10 min; (b) Tool wear 20 min; (c) Tool wear 30 min; (d) Tool wear 40 min; (e) Tool wear 50 min.
2.2. Influence of Spindle Speed on Tool Wear
In the cutting process, the spindle speed has the most direct influence on the tool wear. It can be seen from Fig.6 that under the condition of continuous cutting for 30min, the tool wear increases with the increase of spindle speed. Especially when \( n = 10000 \text{r} / \text{min} \), the tool wear is more severe than the first three. This phenomenon is due to the fact that Ti6Al4V material itself is a kind of hard to process material, and chip separation is difficult. With the increase of the spindle rotation, the front and back face of the tool increase, The longer the friction contact time between tool and workpiece in unit time is and the more intense the friction is, the higher the cutting temperature will be. It makes the sticking wear and diffusion wear of the cutting tool serious, and even the phenomenon of edge collapse.

![Figure 6. Wear of tool front and back face with different spindle speed](image)

3. Analysis of the Influence of Tool Wear on Cutting Process

3.1. Effect of Tool Wear on Chip
Tool wear has a direct impact on chip forming. The chip forming process is essentially an extrusion process. In the process of extrusion, the cut metal mainly undergoes shear slip deformation and forms chips. When cutting plastic materials, when the workpiece is extruded by the cutter, the stress and strain inside the material increase gradually as the cutter continues to cut in. When the resulting stress reaches the yield point of the material, slip begins to occur. The micro morphology of chips and chips formed in different time of continuous cutting wear is shown in Fig.7. It can be seen from the figure that when the tool wear time is 10-30min, the curl degree of chips gradually increases, and the chip forming is relatively stable during cutting. When the continuous cutting reaches 40 minutes, it is the critical point of normal wear and severe wear, and the chips can not form spiral chips. It shows that when the tool cutting reaches the critical point of severe wear, the tool wear starts to increase, the cutting temperature starts to rise sharply, which changes the stable state of chip forming, leading to irregular chip shape. In the figure, the rectangular frame shows the local micro morphology of chips. It can be seen from the figure that under the condition of tool wear time of 10-40min, the chip extrusion fringe is perpendicular to the chip outflow direction, and the fringe protrusion is parallel, the chip contact surface is relatively flat, and the scratch is not obvious. This is because the 10-40min tool wear is the initial and normal wear stage, and the friction coefficient between the tool and the cutting layer of Ti6Al4V material is low during cutting, the deformation of the chip is small, the cutting process is relatively stable, and the stripes extruded from the chip surface are relatively regular and parallel. When the tool wear reaches 50 minutes, it is a severe wear stage. The protruding stripes perpendicular to the chip flow out direction are plush, the stripes are distorted, and the scratches on the chip contact surface are obvious and deep. This is due to the large wear of the cutting edge, and even the phenomenon of chipping and chip bonding occurs when cutting Ti6Al4V. When the chips flow, the bonded particles on the cutting edge will scratch the chips. Due to the sharp increase of cutting
temperature, the material properties of Ti6Al4V material soften, the chips can not be formed regularly, and the final extrusion part presents a plush state.

(a) Tool wear for 10min to cut chip; (b) Tool wear for 20min to cut chip; (c) Tool wear for 30min to cut chip; (d) Tool wear for 40min to cut chip; (e) Tool wear for 50min to cut chip.

Figure 7. Influence diagram of different tool wear on chip forming when n = 4000r/min, F= 800mm/min, ap = 50μm

3.2. The Influence of Tool Wear on Cutting Temperature
The cutting temperature at the tool tip directly affects the service life of the tool. It can be seen from Fig.8 that the cutting temperature increases gradually when the tool wear time is 10min-50min. This is because the degree of tool wear is directly related to the stability of chip separation during cutting. The greater the wear is, the greater the friction between the blade and the cutting layer is in unit time, and the higher the tip temperature will be. However, when the tool wear time reaches 40-50min, the tool is in the stage of severe wear, in this stage, the wear of the blade surface becomes sharply larger. This leads to the sharp increase of friction between the tool and the cutting layer, which directly affects the stable state of chip separation. In this case, the heat can not be dissipated in time, so the cutting temperature rises sharply.

Figure 8. The influence of different wearing tools on cutting temperature

3.3. The Influence of Tool Wear on Cutting Force
The cutting force is based on the chip deformation process. The degree of tool wear has a direct impact on the cutting force produced in the cutting process. Different degrees of tool wear will cause obvious changes in material softening and deformation during cutting. Fig.9 is the cutting diagram when the tool wear time is 10min-50min, with the increase of tool wear time, the cutting force of each
stage gradually increases, the degree of tool wear is directly related to the stability of chip separation during cutting. The larger the wear is, the greater the friction between the front and back face of the cutting edge and the cutting layer is, the higher the temperature will be. However, when the tool wear time reaches 40-50min, the tool is in the stage of severe wear. In this stage, the tool edge wear increases sharply, and the front and back face of the tool will bond or even break. As a result, the friction between the tool and the cutting layer increases sharply, the temperature increases, the chip separation cannot reach a stable state, and the final cutting force increases.

![Figure 9. Cutting force diagram of different tool wear time](image_url)

3.4. Influence of Tool Wear on Residual Stress of Cutting Surface
The degree of tool wear has a great influence on the residual stress of machined surface. With the increase of tool wear time, the residual stress of machined surface becomes larger. It can be seen from Fig.10 that when the tool wear time is 10-50 min, the residual stress of machined surface layer shows an increasing trend, This is because the degree of tool wear is directly related to the stability of chip separation during cutting. The larger the wear is, the greater the friction between the cutting edge and the cutting layer is. The cutting force and temperature of the interaction between the cutting edge and the cutting layer will increase, and the pressure stress of the machined surface will increase. However, when the tool wear time reaches 40-50min, the tool is in the stage of severe wear. In this stage, the tool edge wear increases sharply, which leads to the sharp increase of friction between the tool and the cutting layer, the increase of temperature, the failure of chip separation to reach a stable state, and the increase of residual stress on the machined surface.

![Figure 10. The influence of tool wear time on the residual stress of cutting surface](image_url)

3.5. The Influence of Tool Wear on Cutting Surface Roughness
The degree of tool wear is directly related to the surface roughness of parts. It can be seen from Fig.11 that with the increase of tool wear time, the cutting surface roughness obtained in each stage decreases
first and then increases. This is because when the tool wear time is 10min, the tool is in the initial wear stage. In this stage, due to the height difference between the blades, this stage is not the best cutting stage, and it cannot achieve the best cutting coupling state, so the surface roughness will not be the lowest. However, the surface roughness becomes smaller when the wear time is 10-30min. However, when the tool wear time is 30-40 min, the surface roughness becomes larger. This is because when the tool wear time is 40 minutes, it is in the critical stage of normal wear and severe wear. The tool edge wear is larger, the friction between the blade surface and the cutting layer is larger, and the chip separation cannot reach a stable state. Therefore, when the tool wear time is 50 minutes, the surface roughness of the machined surface begins to increase dramatically.

![Figure 11. The influence of tool wear time on cutting surface roughness](image)

3.6. Influence of Tool Wear on Cutting Surface Quality
The degree of tool wear is directly related to the machining surface quality of parts. From Fig.12, it can be seen that when the tool wear time is 10min, the machined surface quality has obvious tool grain and large edge burr. This is because there is a height difference between the cutting edges in the initial wear stage of the tool, which does not reach the optimal cutting coupling state of the cutting edge, so the machining surface of the tool and the edge burr are relatively obvious. When it comes to the normal wear stage, the machined surface quality is gradually smooth. However, when the tool wear time is 40 min, the burr on the machining edge begins to increase, because this time is in the critical stage of normal wear and severe wear. The wear of the cutting edge is bigger, the friction between the cutting surface and the cutting layer is bigger, the temperature is higher, the chip separation can not reach a stable state, and the big burr will be formed at the separation edge. Therefore, when the tool wear time is 50 minutes, the machined surface quality begins to decline sharply and the edge burr is thick.
4. Conclusions
According to the wear mechanism and experimental analysis of Ti6Al4V micro milling tool, the conclusions are as follows:

(1) Through the energy spectrum analysis of the damaged parts of the front and back face of the tool by scanning electron microscope, the change of the element composition in the specific area was detected to analyze: in the process of Ti6Al4V milling, the tool had oxidation wear, adhesive wear and diffusion wear;

(2) The spindle speed has a direct impact on the degree of tool wear. Under the condition of continuous cutting for 30 minutes, the tool wear increases with the increase of spindle speed;

(3) Under the condition of tool wear time of 10-40min, the chip extrusion fringe is perpendicular to the chip flow out direction, the fringe protrusion is parallel, the chip contact surface is relatively flat, and the scratch is not obvious; while when the tool continuously cuts for 50min and reaches the stage of severe wear, the protrusion fringe perpendicular to the chip flow out direction is fluffy, the fringe is twisted, and the scratch on the chip contact surface is obvious; Obvious and deep;

(4) With the increase of tool wear time, the cutting force of each stage is larger; with the increase of tool wear time, the residual stress of machined surface is larger; with the increase of tool wear time, the surface roughness of each stage decreases first and then becomes larger, while the normal wear stage of tool cutting for 30min is normal. The surface roughness is the smallest when the cutting tool is continuously worn for 50 minutes, and the cutting temperature increases with the wear time;

When the tool continuous cutting wear time is 10min, the machined surface quality grain is obvious and the edge burr is large. When the tool continuous cutting wear time is 40min, the machined edge burr starts to increase, but when the tool continuous cutting wear time is 50min, the machined surface quality begins to decrease sharply and the edge burr is thick.

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6. References
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