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# Dimension Accuracy and Surface Integrity of Creep Feed Ground Titanium Alloy with Monolayer Brazed CBN Shaped Wheels

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**Abstract**

Titanium alloy tenon is creep feed ground with monolayer brazed cubic boron nitride (CBN) shaped wheels. The dimension accuracy of the tenon is assessed and the results indicate that it completely meets the requirement of blade tenon of aero-engine. Residual stresses, surface roughness, microstructure and microhardness are measured on ground surfaces of the specimen, which are all compared with that ground with vitrified CBN wheels. Under all the circumstances, compressive residual stress is obtained and the depth of the machining affected zone is found to be less than 40 μm. No phase transformation is observed at depths of up to 100 μm below the surface, though plastic deformation is visible in the process of grain refinement. The residual stress and microhardness of specimens ground with brazed CBN wheels are observed to be lower than those ground with vitrified ones. The arithmetic mean roughness ($R_a$) values obtained are all below 0.8 μm.

*Keywords:* creep feed; dimension accuracy; surface integrity; monolayer brazed CBN grinding wheel; titanium alloys

## 1. Introduction

Titanium alloys are widely employed in such fields as aerospace, automobile and defense industry because of their excellent mechanical strength and resistance to surface degradation[1-2]. However, the favorable physical and chemical properties that make these alloys suitable for many applications also result in the difficulty with which they are machined, especially the critical surface damage of ground specimen. Superabrasive wheels have been one of the most popular tools to machine titanium alloys[3-4]. Being regarded as the substitute for electroplated wheels, the monolayer brazed cubic boron nitride (CBN) grinding wheels provide higher crystal exposure, bond uniformity and better grit retention[4-6]. Moreover, the grits are hardly to be pulled out, and the inter-grit chip space is larger and can thereby contain more coolant and take more heat away. At the same time, the combination of grit material, brazing material as well as core material is characterized by high thermal conductivity to ensure heat dissipation from the grinding tool tip of the grits, which will benefit the finished surface integrity, especially in creep feed grinding for its long contact zone.

Although some research has been conducted on the grinding of titanium alloys using monolayer brazed CBN wheels[4,7], relatively fewer studies have been dedicated to complex profile creep feed grinding. As a matter of fact, however, titanium alloys tend to be complex in profile, whose characteristics such as dimension deviation, roughness, type and magnitude of residual stresses, hardness alterations and plastic deformation affect loading capacity, wear behavior and fatigue resistance. The present investigation was undertaken on Ti-6Al-4V alloy in order to evaluate the ground surface integrity of a complex profile while using a monolayer brazed CBN grinding wheel, which will expand the application of brazed CBN grinding wheels, and a vitrified CBN wheel was used for comparison.

## 2. Experimental

According to the lamina tenon of some aero-engine, the profile of the specimen that would be machined in this experiment was designed as shown in Fig.1. Creep feed profile grinding experiments were carried out on a MKL7150×16/2 CNC Profile Grinder (Hangzhou Machine Tool Group Co., Ltd. China). Two types of CBN shaped grinding wheels, monolayer brazed and

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vitrified, were used in the experiments. The titanium alloy Ti-6Al-4V used for the experiments is in annealed condition. Further experimental conditions are shown in Table 1.

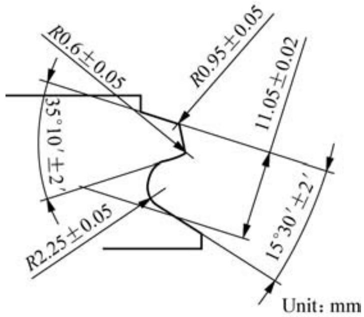



Fig.1 Designed profile.

**Table 1 Experimental conditions**

| Item | Description |
|---|---|
| Grinding wheel | Monolayer brazed CBN wheel<br>Vitrified CBN wheel (150% concentration) |
| Abrasive grit material | YBN-65 (80/100 ANSI mesh size) |
| Wheel diameter $d_s$/mm | 175 |
| Cutting velocity $v_c$/(m·s$^{-1}$) | 18.5 |
| Table speed $v_w$/(mm·min$^{-1}$) | 100 |
| Depth of cut $a_p$/mm | 1.0 |
| Coolant | 5% solution of oil-in-water emulsion<br>90 L/min<br>0.8 MPa |

The monolayer brazed CBN grinding wheel was self developed and self fabricated, and the grit distribution is shown in Fig.2. It needs to be mentioned that because of the difficulty and high cost of dressing, the profile of the vitrified CBN shaped wheel was not identical to the designed profile.

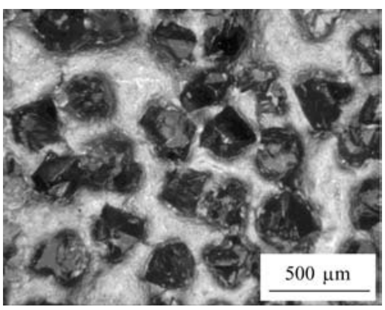



Fig.2 Grit distribution of brazed CBN grinding wheel.

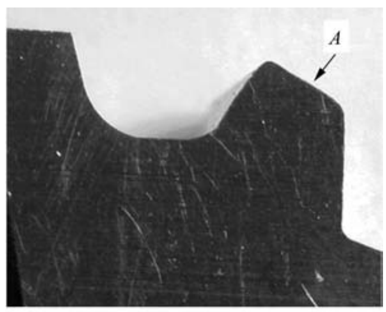
Dimension accuracy was assessed by measurement taken on 6 points by means of a coordinate measuring machine and a KH-7700 3D viewer. Surface roughness measurements were carried out with a surface roughness tester on 6 points with a cut-off length of 1.75 mm and measurement traces were perpendicular to the grinding direction. In doing so, each of the 6 points was measured for three times before an average was obtained. The metallographic sample was etched for about 2-5 s with a mixture of HF and $HNO_3$, and the volume ratio was 5:95. Microstructure was analyzed with optic microscopy. Microhardness was measured by a HXS-1000A microhardness tester. The load adopted was 100 g with a holding time of 15 s. Residual stress measurements were made on the surface after grinding using X-rays by the $\sin^2\psi$ technique for biaxial stresses, where $\psi$ is the angle of incidence. Ti(α+β) {4 1 2} reflection and CuKα radiation were chosen. The penetration of CuKα was 5 μm, giving a peak at $2\theta\approx140.86°$, where $\theta$ is the angle of diffraction. Reflections were recorded in a $2\theta$ measuring range of 130°-170°.

## 3. Results and Discussion

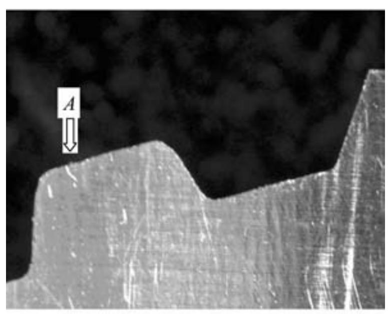
### 3.1. Dimensions

The photographs of ground specimens are shown in Fig.3, in which the profiles of both specimens are smooth and clear (1# specimen was ground by brazed CBN wheels, and 2# was ground with vitrified CBN wheels). The dimensions of specimens ground with monolayer brazed CBN wheels were measured and the results are listed in Table 2, which indicates that the accuracy of profile completely meets the requirement of design (see Fig.1). Other dimensions were also measured, and all the deviations are within tolerance.

The profile wear is manifested as the changes in the shape of the profile formed on the grinding wheel as a result of wear during the grinding process[8]. In creep feed profile grinding, the profile wear as well as radial




(a) 1# specimen




(b) 2# specimen

Fig.3 Photograph of ground specimens.

**Table 2 Main dimensions of specimens ground by brazed CBN wheels**

| Dimension | | No. of specimen 1 | 3 | 5 | 10 |
|---|---|---|---|---|---|
| Distance /mm | Measured | 11.07 | 11.06 | 11.05 | 11.05 |
| | Designed | 11.05±0.02 | | | |
| | Deviation | 0-0.02 | | | |
| Corner radius /mm | Measured | 2.23 | 2.24 | 2.26 | 2.26 |
| | Designed | 2.25±0.05 | | | |
| | Deviation | −0.02-0.01 | | | |
| Angle | Measured | 35°8′ | 35°8′ | 35°10′ | 35°10′ |
| | Designed | 35°10′±2′ | | | |
| | Deviation | −2′-0 | | | |

wear affects the shape and accuracy of ground profiles. Thus, the profile wear of the wheel can be reflected from the changes of dimensions of the ground specimen. As can be seen from Table 2, the main dimensions of ground tenons remain nearly constant since the fifth one, i.e. the brazed CBN grinding wheel gives less profile wear and hence more excellent form retention. Therefore, brazed CBN wheels are suitable for applications with high dimensional accuracy in the creep feed profile grinding of titanium alloy.

The dimensions of the specimens ground by vitrified CBN wheels were not measured for the reason that the profile of vitrified ones was not identical to the brazed CBN wheels.

### *3.2. Surface roughness*

The surface roughness is a variable often used to describe the quality of ground surfaces as well as to evaluate the competitiveness of the overall grinding system, which is represented by the arithmetic mean value $R_a$, the root mean square average $R_q$, and the maximum roughness height $R_t$. Generally, the longitudinal surface roughness has a lower value than the traverse surface roughness, then the latter is more frequently used in industry. Therefore, $R_a$ of all specimens after grinding was measured and the results are shown in Fig.4.

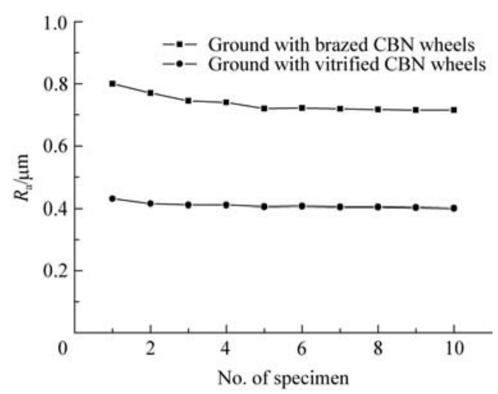



Fig.4 Surface roughness of specimens after grinding.

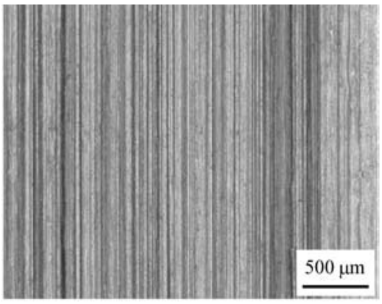
For the specimens ground with brazed CBN wheels, roughness tends to decrease with continuous grinding until the fifth specimen, at which point the roughness remains nearly constant at about 0.75 μm. On the other hand, roughness of specimens ground with vitrified CBN wheels stabilizes at about 0.40 μm since the second one, and the $R_a$ of the tenth specimen only decreases slightly in comparison with the second one. Therefore, the wear resistance of CBN wheels is excellent in the creep feed grinding of titanium alloy.

The distance of the grit tips from the newly brazed wheel substrate surface is unequal without truing and dressing, though some new technologies were used to control the grit protrusion in the present study. In the initial stage of grinding, these high grits prevented the shorter ones from participating. This results in less overlapping cuts of grit leading to a transverse surface roughness, sometimes substantially higher than the acceptable value. Absence of the cross feed during profile grinding worsens the situation. So the roughness of specimens ground with a newly brazed CBN wheel, about 0.80 μm, is quite higher than that ground with dressed vitrified CBN wheel, about 0.43 μm. Since most grits of brazed wheel even have protrusion height with continuous grinding, almost all grits gradually become active and participated grinding, hence the roughness decreases little by little until it becomes a constant at about 0.75 μm.

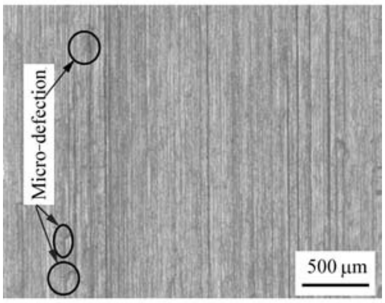
The values of $R_a$ obtained are below 0.80 μm for all specimens, which meet the requirement of lamina tenon used in aero-engine and is appropriate for surfaces having to slide over each other such as high performance gears, sliding plates, guides, etc.

### *3.3. Morphology and microstructure*

At surface *A*, the morphology of ground surface and the microstructure of the cross section which is perpendicular to grinding direction, were studied using a KH-7700 3D viewer. In Fig.5, the typical morphology of ground surface *A* is shown. Comparing the morphologies ground with two types of CBN wheels, surface mirco-defections are found on the surface of 2# specimen (see Fig.5(b)), which does not seem to occur on that of 1# specimen (see Fig.5(a)). As is well known, a single abrasive grit plays three roles in grinding: rubbing, plowing and cutting[9]. With rubbing, the elastic/plastic deformation occurs without a noticeable material removal. In plowing, the material is plastically extruded in both the grinding direction and in the direction perpendicular to it. Material is mainly removed by shearing via the cutting action that apparently depends on the sharpness of the abrasive cutting edges. The morphology generation of a ground surface is influenced by several factors including the characteristics of the used wheel, the properties of the workpiece material and the grinding conditions[10]. In the present study, the same material was ground on the same machine with nominally the same grinding conditions, thus the causes for the above morphology differences can be reasonably attributed to the wheel performance during the material removal process.




(a) 1# specimen

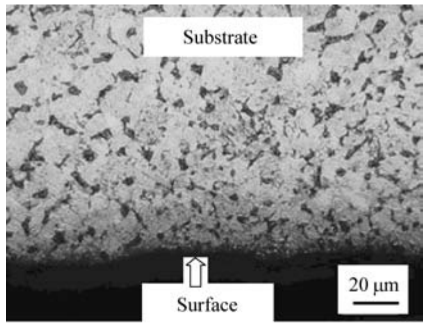



(b) 2# specimen

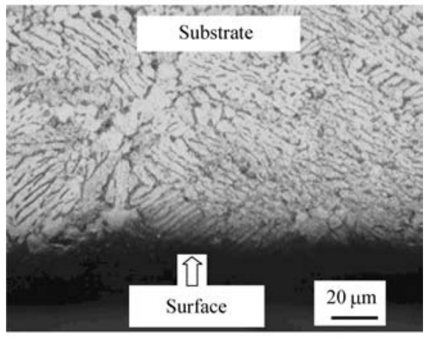
Fig.5 Morphology of ground surface.

The above result also attributes to the effective coolant flow of the brazed wheel. It is well known that the coolant plays three major roles in grinding: heat removal, lubrication and chip cleaning (prevention of the grinding wheel surface from chip loading). While creep feed grinding with vitrified wheels, the chips were hardly completely cleaned, thus some chips peeled off from the wheel surface might re-enter the grinding zone. Under a high pressure, these chips could plough the material and result in defection on the finished surface. Due to the larger inter-grit chip space while grinding with brazed wheels, more coolant enters the grinding zone, which leads to more effective cooling and better lubrication, promotes the chip cleaning and thus prevents the re-entrance of chips into the grinding zone. Consequently, the sharpness of the active grits is maintained. Ultimately, the brazed CBN wheel is found to allow a higher depth of cut and minimizes the frequency of wheel dressing and truing.

The microstructures of the cross section perpendicular to the grinding direction are illustrated in Fig.6, which shows that there is no microcrack in the ground surface/subsurface layer. In contrast to the substrate, the grains of the ground surface layer are slightly finer which results mainly from the sliding, plowing and cutting during the grinding process. The distortion of the crystal lattice tends to strengthen the resistance of transmutation and thus results in work-hardening of the surface layer. If the degree of work-hardening is excessive, it will undoubtedly lead to the degradation of the performance of substrate materials.




(a) 1# specimen




(b) 2# specimen

Fig.6 Microstructure of cross section of ground specimens.

### 3.4. Microhardness

In order to ascertain the grinding affected zone, the microhardness on the section perpendicular to surface layer and grinding direction was measured, as shown in Fig.7(a), in which the angle is about 10° between the line of measure points and the ground surface $A$, and the perpendicular distance of each two points is 5 μm. The results are shown in Fig.7(b) and Fig.7(c), where HK is the Knoop hardness. In general, depending on the temperature of the cutting process, annealing of the workpiece may occur during grinding, causing softening close to the finished surface. The values of microhardness are both maximum on very surface, and tend to decrease in the sub-surface layer, which indicates that softening does not occur, i.e. the temperature of grinding zone is lower than the temperature of phase transformation in the grinding process of titanium alloy with CBN wheels. The microhardness of the ground surface of 1# specimen (about HK 2 800 MPa) rises by 30.2% in comparison with that of the substrate (about HK 2 150 MPa), while that of 2# specimen (about HK 2 900 MPa) rises by 36.1%, higher than the specimen ground by brazed CBN wheels. In both cases, the depth of work-hardening is less than 40 μm.

As the monolayer brazed CBN grinding wheel provides higher grit exposure than vitrified ones, its inter-grit chip space is larger, hence there is more coolant to remove more heat from the contact zone. Meanwhile, the higher thermal conductivity of brazing material compared with that of the vitrified bond is characterized by ensuring heat dissipation from the grinding tool tip of the grits. Then the surface temperature ground with braze CBN wheels is lower than that ground with vitrified wheels, which results in slighter thermal effect and less thermal damage.

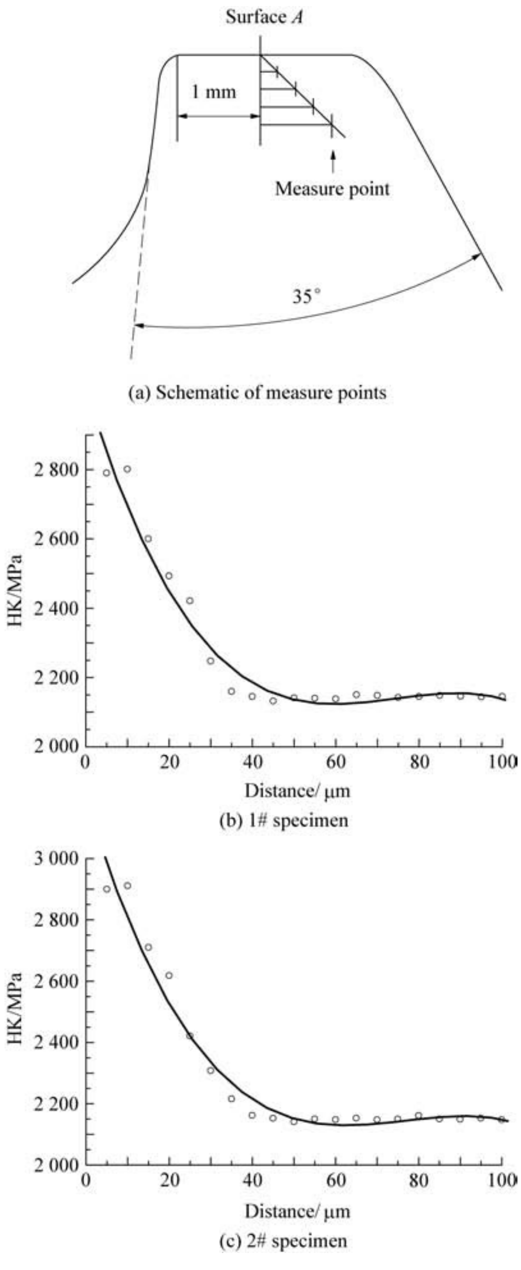



Fig.7 Microhardness of ground surface.

### 3.5. Surface residual stress

Fig.8 shows the mean value of measured surface residual stresses along the grinding direction. It can be seen that a high compressive surface stress (about –245 MPa) is induced by the vitrified wheel. When using the brazed wheel, the surface residual stress is less compressive (about –128 MPa).


Fig.8 Surface residual stress of ground specimens.

Residual stress generation in grinding is caused by three principal sources[11]: mechanically-induced plastic deformation, thermal deformation and phase transformation. In the present study, no phase transformation is found on the surface and subsurface of both specimens (see Fig.6). Also the mircohardness of the ground specimens is obviously higher than the ones prior to grinding (see Fig.7), which may be due to the cold hardening caused by grinding. The aforementioned observations show that mechanical and thermal deformations are the sources of residual stress formation here.

In abrasive processes, the specimen-wheel contact zone can reach very high temperature gradients, which produces tensile residual stresses during the rapid cooling process upon the contraction of the heated area (thermal effect)[12-13]. At the same time, surface and sub-surface layers get plastically deformed during grinding, which leads to compressive stresses[12].

The fact that residual grinding stresses are all compressive highlights the preponderance of mechanical over thermal effects, which suggests that the temperature gradients are very low while using CBN wheels due to their high thermal conductivities.

## 4. Conclusions

The titanium alloy Ti-6Al-4V was creep feed profile ground with a newly developed brazed CBN wheel and the dimension accuracy and surface integrity were investigated and compared with those of a representative vitrified CBN wheel. The main results obtained in this study are summarized as follows:

(1) The surface integrity of titanium alloy ground with monolayer brazed CBN shaped wheels completely meets the requirement of lamina tenon of aero-engine.

(2) The dimension deviation of specimens ground with monolayer brazed CBN shaped wheels is within tolerance.

(3) For both CBN wheels, machining affected area can be appreciated at depths of up to 40 μm below the surface, as a consequence of the plastic deformation produced during grinding.

(4) The microhardness and surface residual stress of specimens ground by monolayer brazed CBN wheels

are lower than those ground by vitrified CBN wheels.

(5) The arithmetic mean roughness is always below 0.80 μm for all specimens, representing a good quality surface for most industrial applications as well as lamina tenon of aero-engine.

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