Investigation on the machinability of metastable $\beta$ titanium alloy M28

Yifan Jiang$^1$ · Hui Tian$^2$ · Jia Yin$^2$ · Yinfei Yang$^1$ · Guolong Zhao$^1$ · Liang Li$^1$

Received: 25 August 2021 / Accepted: 23 May 2022 / Published online: 8 June 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
Oriented to the application of new generation strategic aircraft, M28 (Ti-4Al-5Mo-5 V-6Cr-1Nb) is a novel metastable $\beta$ titanium alloy with outstanding strength. The research on the machining of such hard-to-machine material remains inadequate. To investigate the machinability of M28, milling experiments were made with the uncoated WC–Co carbide insert. The cutting force and tool life of M28 were compared with those of Ti-6Al-4 V in varying cutting speeds. The tool wear mode was also analyzed. The cutting force of M28 increases with cutting speed significantly, especially in high-speed cutting where it can reach as high as 132% of that of Ti-6Al-4 V. The “transgranular cut” of M28 contributes to the high cutting force. A much shorter tool life in cutting M28, ranging from 0.88% to 13.82% of that of Ti-6Al-4 V, was found in the experiment. Serious edge chipping occurred at the normal cutting speed as the result of stress concentration and abrasion of the secondary $\alpha$ precipitation. In high-speed cutting, chip adhesion, comb cracks, and tool plastic deformation were found at the edge as the result of the high temperature. In addition, the semi-crater at the worn edge tip was formed by the interaction of high-frequency cutting impact, carbide thermal softening, and diffusion wear. A better understanding of the machinability of M28 is conducive to the improvement in manufacture in the aviation industry.

Keywords High-speed milling · $\beta$ titanium alloy · Titanium alloy machinability · Carbide tools · Tool wear

1 Introduction

The new generation of aircraft calls for a new generation of material. Therefore, novel titanium alloys are developed to satisfy the more demanding requirement of material performance in strength-to-weight ratio, strength, fatigue strength, corrosion resistance, etc. [1–3]. Increasingly more attention has been put on metastable $\beta$ titanium alloys since these alloys can be hardened to extremely high strength and their complex microstructure enables the combination of both high strength and high toughness [4, 5]. $\beta$ titanium alloys show good application values in the aircraft component such as landing gears, load-bearing fuselage components, high-lift devices of the large aircraft, plug-and-nozzle assemblies of the jet engine, and main bolted rotor head of helicopters [1–3, 6, 7].

However, the outstanding material performance poses a challenge to aircraft manufacturing. $\beta$ titanium alloys have been reported to be the most difficult to machine among all titanium alloys since 1970s [8]. $\beta$ titanium alloys are hard to machine due to the elevated cutting temperature, high cutting forces, and, particularly, the rapid tool wear [9–13]. The machining efficiency of them is restricted by the tool life. For instance, to achieve an industry employed tool life (15 min), the cutting speed for machining Ti-5Al-5Mo-5 V-3Cr, a typical $\beta$ titanium alloy, was nearly 56% lower than that for machining Ti-6Al-4 V [10]. The tool wear in cutting $\beta$ titanium alloys, including Ti-5Al-5Mo-5 V-3Cr, Ti-10 V-2Fe-3Al, and Ti-3Al-8 V-6Cr-4Mo-4Zr ($\beta$C alloy), is mainly classified as abrasion and adhesion [7, 10, 14–16]. The micro-chipping at the cutting edge was generated in the machining of aged Ti-10 V-2Fe-3Al [12, 15]. Chip adhesion still occurs even various cooling and lubrication methods were applied in machining $\beta$ titanium alloys, including liquid nitrogen cryogenic cooling, high-pressure fluid cooling, minimum quantity lubrication (MQL) [17], and carbon dioxide snow jet cooling [7].

As a novel titanium alloy with an outstanding strength as high as 1350 MPa [2], M28 (Ti-4Al-5Mo-5 V-6Cr-1Nb) is applied to the load-bearing fuselage component of the new...
generation strategic aircraft. Besides the common features of titanium alloys, such as poor thermal conductivity, high chemical reactivity, and low modulus of elasticity [12, 18], the machining of M28 is subject to the specific property of metastable $\beta$ titanium alloys as well. Metastable $\beta$ titanium alloys can be strengthened to extremely high strength levels of more than 1400 MPa, which is greater than that of common $\alpha+\beta$ titanium alloys (750 – 1000 MPa) as the result of proper heat treatment like aging and solution [4, 19]. Additionally, the diffusivity of most tool material into $\beta$ phase titanium was two to three orders of magnitude higher than those in $\alpha$ phase titanium [20], which weakens the tool and accelerates the tool wear. The machinability evaluation is the cornerstone of machining efficiency improvement. The knowledge about the cutting tool wear behavior in machining M28 will also contribute to the understanding of the ultra-high strength titanium alloy cutting process.

In this study, milling experiments of M28 were conducted with the uncoated WC–Co carbide insert to investigate its machinability. To research the wear mechanism of high-speed cutting of M28, microscopic observations of the worn edge were made. In addition, the worn insert was sectioned to analyze the element distribution across the tool–chip interface in the wear area.

## 2 Experiment procedures

### 2.1 Workpiece materials

M28 (Ti-4Al-5Mo-5 V-6Cr-1Nb) is a novel metastable $\beta$ titanium alloy [2]. The chemical composition of the as-received M28 material is listed in Table 1. $\beta$ stabilize elements such as V, Mo, and Nb play the role of strengthening elements due to their high solid solubility in $\beta$ phase [21].

Molybdenum equivalent ($Mo_{Eq}$) is utilized for ranking the $\beta$ phase stability of various compositions, indicating the capacity to obtain an ultimate strength and hardness in the aged condition [10, 22]. Its calculation equation is shown in Eq. (1) [23]. In general, a $Mo_{Eq}$ of 10% is required to stabilize the $\beta$ phase upon quenching to room temperature [24]. The nominal composition of the M28 alloy, Ti-4Al-5Mo-5 V-6Cr-1Nb, has a $Mo_{Eq}$ of 14.23%, which is much larger than that of Ti-6Al-4 V (a typical $\alpha+\beta$ titanium alloy) and Ti-10 V-2Fe-3Al (a typical $\beta$ titanium alloy), as shown in Fig. 1. Therefore, M28 can retain the body-centered cubic (BCC) structure at room temperature.

$$Mo_{Eq} = Mo + 0.67V + 0.44W + 0.28Nb + 0.22Ta + 2.9Fe + 1.6Cr − Al$$  

Mechanical properties of metastable $\beta$ titanium alloys can be tailored by controlling the microstructure via heat treatments. Figure 2a shows the metallographic microstructure of M28, where coarse $\beta$ grains and primary $\alpha$ phase ($\alpha_p$) were found. Through aging treatment, fine secondary $\alpha$ phase ($\alpha_s$) uniformly precipitated in the coarse equiaxed $\beta$ grains; the SEM image of these fine $\alpha_s$ is shown in Fig. 2b. The comparison among the strength of M28, Ti-6Al-4 V, and Ti-10 V-2Fe-3Al is shown in Fig. 3. The strength of aged M28 is as high as 1350 MPa, much higher than that of Ti-6Al-4 V and Ti-10 V-2Fe-3Al.

### 2.2 Cutting tool, machine tool, and cutting parameters

On-shelf uncoated cutting inserts in ISO grade K40 were utilized for the experiment. The composition of this carbide is mainly WC and Co (6%, wt). The geometry of the insert is listed in Table 2. The radius of the original sharp cutting edge was measured by the optical 3D measurement system (InfiniteFocusG5, ALICONA GmbH). The tool diameter is 25 mm. In the experiment, only one insert was equipped on the tool each time in the cutting experiment.

The experiments were carried out on a high-speed machining center Mikron UCP 710, supplying a maximum power of 16 kW and a maximum spindle speed of 18,000 rpm. The cutting force of milling M28 was tested at varying cutting speeds $v_c$ and feed per tooth $f_z$, respectively, with the constant cutting depth $a_p$ and cutting width $a_e$. The cutting parameters of the tests are listed in Table 3. Cutting speed is considered as the priority factor for tool wear [25]. In this research, contrast tests of milling M28 and
Ti-6Al-4V about the influence of the cutting speed on the tool wear were carried out. The cutting parameters of the contrast tool wear test are listed in Table 4. A 0.3 mm width of the flank wear VB was set as the tool wear criteria. The cutting length \( L_c \) of each insert was documented as the flank wear reaches the wear criteria.

MQL was utilized for cooling and lubrication in all cutting experiments. With 6 bars of air pressure, pulverized fatty alcohol-based cutting oil (Blaser Vascomill MMS FA 1) was sprayed on the tool at a rate of 30 ml/h.

**Fig. 2** Metallographic image of aged M28 a primary \( \alpha \) phase and coarse \( \beta \) grains (optical microscopy) and b secondary \( \alpha \) phase (SEM)

**Fig. 3** Strength of three kinds of titanium alloys [1, 2]

| Rake angle \( \gamma \) | Clearance angle \( \alpha \) | Cutting edge angle \( \alpha_c \) | Helix angle \( \beta \) | Radius of edge \( r \) |
|-----------------------|-----------------------------|-----------------------------|----------------|------------------|
| \(-25^\circ\)           | 15°                         | 90°                         | 0°             | 4.08 \( \mu \)m |

Table 2 Geometry parameters of the K40 insert

Table 3 Cutting parameters of the M28 cutting force test

| \( v_c \) (m/min) | \( f_z \) (mm/z) | \( a_p \) (mm) | \( a_e \) (mm) |
|------------------|----------------|-------------|-------------|
| 45               | 0.1            | 5           | 1           |
| 60               | 0.1            |             |             |
| 100              | 0.1            |             |             |
| 200              | 0.06           |             |             |
| 200              | 0.08           |             |             |
| 200              | 0.1            |             |             |
| 200              | 0.12           |             |             |
| 200              | 0.15           |             |             |
| 300              | 0.1            |             |             |

Table 4 Cutting parameters of the tool wear contrast test (M28 & Ti-6Al-4 V)

2.3 Measurement and detection

Cutting forces in an orthogonal coordinate (Fx, Fy, Fz) were measured by a piezoelectric dynamometer (Kistler 9265B) and the charge amplifier (Kistler 5019A) at the sampling rate of 10 kHz. Figure 4 illustrates the experiment setup, the cutting force in the X-direction (Fx) was parallel to the feed speed \( v_f \), the cutting force in Y-direction (Fy) was parallel to the cutting width \( a_e \), and the cutting force in the Z-direction (Fz) is in the spindle direction. The cutting force signal was recorded through an A/D converter on a standard desktop PC with the data acquisition and processing software Dynoware. In this paper, the mean value of the maximum force data is counted as the cutting force value.

A CCD microscope (CXSP-2KCH) was utilized to observe and measure the flank wear in the experiment. To uncover the worn edge under the titanium material adhesion, the adhesion material was pickled by the hydrofluoric etchant. The microscopic observation and element detection of the worn edge were carried out by a Hitachi TM 3000 scanning electron microscope (SEM) with an energy-dispersive spectrometer.

| \( v_c \) (m/min) | \( f_z \) (mm/z) | \( a_p \) (mm) | \( a_e \) (mm) |
|------------------|----------------|-------------|-------------|
| 45               | 0.1            | 5           | 1           |
| 100              |                |             |             |
| 200              | 0.06           |             |             |
| 200              | 0.08           |             |             |
| 200              | 0.1            |             |             |
| 200              | 0.12           |             |             |
| 200              | 0.15           |             |             |
| 300              | 0.1            |             |             |
(EDS) system (Oxford Instruments). To further investigate the tool wear, a worn insert was sectioned perpendicular to the cutting edge by electrical discharge machining (EDM) to reveal the inner part of the worn edge, as shown in Fig. 5. The sectioned insert was encapsulated in the conductive resin and polished with diamond spray.

3 Results

3.1 Cutting force

Originating from the interaction of the cutting tool and workpiece material, the cutting forces directly reflect the cutting process; hence, the knowledge of it is beneficial to process design. Figure 6 shows the influence of the cutting speed on the cutting force. Fy is the dominant proportion of the 3-dimensional cutting forces, following Fx. Fy rises considerably with the increasingly growing cutting speed, especially in high-speed cutting ($v_c \geq 100\ m/min$), while the increase in Fx and Fz is not so distinguished. Figure 7 shows the influence of the feed per tooth on the cutting force at $v_c = 200\ m/min$. With the increase in the feed per tooth, Fy rises in an approximate linear pace. Similarly, the increase in Fx and Fz is less significant than that of Fy. Usually, the cutting force is affected by the cross-sectional area of the undeformed chip and the specific cutting force $K_c$ [26]. With a growing feed per tooth, the undeformed chip thickness $h$ increases, resulting in a higher cutting force. Fy mainly originates from the interaction between the side cutting edge and the finished workpiece surface. In metastable $\beta$ titanium alloys, the evolution in microstructure by thermo-mechanical treatments can tailor a lower elastic modulus [19, 22]. In addition, the elastic
modulus of the titanium alloy will further decrease with a rise in temperature [27]. Hence, $F_y$ increases with the higher cutting speed as the result of more serious spring-back on the tool flank face.

A comparison test was made to evaluate the machinability of M28 from the view of cutting force. Figure 8 presents cutting forces of M28 and Ti-6Al-4 V in the experiment. $F_x$ of M28 is almost 85% of that of Ti-6Al-4 V from the cutting speed of 45 m/min to 300 m/min. $F_y$ of M28 at the cutting speed of 45 m/min is nearly 115% of that of Ti-6Al-4 V. However, in high-speed cutting, $F_y$ of M28 shows a percentage rise which will increase as high as 132% of that of Ti-6Al-4 V at the cutting speed of 300 m/min, while $F_z$ of M28 at the cutting speed of 100 m/min is nearly 136% of that of Ti-6Al-4 V. With the cutting speed increasing, $F_z$ of M28 slightly rises to 154%, 143% and 152% of that of Ti-6Al-4 V at the cutting speed of 100 m/min, 200 m/min, and 300 m/min, respectively. The comparison in tool life, as well as the higher cutting force, presents the poor machinability of M28 directly.

3.2 Tool wear

The tool life of milling M28 and Ti-6Al-4 V in the same cutting speed is presented in Fig. 9. The cutting length at a lower cutting speed is longer than that at a higher cutting speed in both the machining of M28 and Ti-6Al-4 V. In the machining of M28, the reduction in the cutting speed brings a significant effect on the tool life as compared with machining Ti-6Al-4 V. For M28 machining, the cutting length at the cutting speed of $v_c$=45 m/min is nearly 495% of that at the cutting speed of $v_c$=300 m/min. The tool life of M28 is considerably poorer than that of Ti-6Al-4 V in the same condition of cutting parameters and tool. The cutting length of milling M28 is nearly 0.88% of that of Ti-6Al-4 V at the cutting speed of $v_c$=45 m/min. In the high-speed cutting, the percentage comes to be 4.02%, 6.21% and 13.82% of that of Ti-6Al-4 V at the cutting speed of $v_c$=300 m/min, 200 m/min, and 300 m/min, respectively. The comparison in tool life, as well as the higher cutting force, presents the poor machinability of M28 directly.

Figure 10 presents the development of tool flank wear of cutting M28 at varying cutting speeds. The increment of the flank wear is rapid in the high-speed cutting, especially at the cutting speed of $v_c$=300 m/min and $v_c$=200 m/min. At the cutting speed of $v_c$=45 m/min, the development of VB is slower than that at the cutting speed of $v_c$=100 m/min before a rapid rise. This is due to the cutting-edge chipping. As the worn edges at varying cutting speeds shown in Fig. 11, there is a distinguishable difference between the wear mode in the normal speed cutting and that of the high-speed cutting. At the cutting speed of $v_c$=45 m/min, large-scale edge chipping occurs with some adhesion material remaining in the broken flank face, as shown in Fig. 11a, while continuous bands of flank wear are formed with significant chip adhesion on it at the cutting speed of $v_c$=100 m/min, $v_c$=200 m/min, and $v_c$=300 m/min, as shown in Fig. 11b–d, respectively. These chip adhesion covers almost all the engaged edge.

The SEM image of the adhesion on the worn tool edge at the cutting speed of 45 m/min is shown in Fig. 12. Cutting edge chipping can be found in the flank face as shown
in Fig. 12a. In the broken area, there exists some amount of adhesion material. The cascading adhesion material, as shown in Fig. 12b, is a part of the flowing chip flow. The irregular edge formed by material chipping in the broken area took the place of the original cutting edge and proceeded with cutting. Figure 13 presents the SEM image of a chip collected in the experiment ($v_c = 45$ m/min); a small piece of carbide was embedded in it.

The SEM image of the worn insert of the high-speed cutting experiment ($v_c = 300$ m/min) is shown in Fig. 14. In the high-speed cutting experiment, the cascading chip flow adhered along the whole engaged cutting edge as shown in Fig. 14a. Comb cracks along the whole engaged cutting edge were revealed after the chip adhesion is etched as shown in Fig. 14b. On the top of the worn edge, there are semi-craters like concave corners, as shown in Fig. 14c.

EDS detection was made to show the spectrum of chemical elements in point A and point B in the high-speed cutting chip adhesion, as shown in Fig. 15a, which are presented, respectively, in Fig. 15b, c. W, C, and Co are found at the chip adhesion indicating the diffusion of carbide material.

Some scattered WC particles are found on the surface of the adhesion chip, as Fig. 16a shows. The chemical elements of a single particle (point C) are presented in Fig. 16b. The major element of it is W and C, while some other elements from M28, including Ti, Al, and V, are also found.

![Fig. 10 Flank wear development in varying cutting speeds ($f_z$ =0.1 mm/z, $a_p$=5 mm, $a_t$=1 mm)](image)

![Fig. 11 Tool wear at varying cutting speeds a $v_c = 45$ m/min, b $v_c = 100$ m/min, c $v_c = 200$ m/min, and d $v_c = 300$ m/min)](image)
In Fig. 17a, the SEM image of the section profile of the insert is presented. In the section profile, a little deviation can be found between the worn rake face (dash line in purple) and the original rake face (solid line in blue), showing the plastic deformation in the edge tip. To observe the worn edge in detail, a magnified image of it is presented in Fig. 17b. There is a little chip adhesion at the edge. The chip–tool contact archway length is nearly 187.15 μm. It can be found that the worn edge is of an irregular round shape, which is approximately composed of two circular arcs with radios 215.41 μm and 250.43 μm, respectively. A semi-crater can be found at the rounded edge as well. The chemical element distribution from the flank face to the inner matrix was detected by EDS line scanning, as Line 1 shown in Fig. 17c. Gradient distributions of W and C are found through the superficial layer of the tool–workpiece interface to the inner matrix. An isolated peak in the Ti spectrum curve is located at approximately 30~40 μm from the flank face with a spectrum curve peak of C. As Fig. 17c shows, the distribution of chemical elements at Line 1 can be divided as the rich carbon layer (RC layer), the diffusion layer and the carbide matrix (WC–Co), from the superficial of the flank face to the inner matrix sequentially. The RC layer ranges about 30 μm from the flank face. The diffusion layer is located beneath the RC layer, covering a width of 20~30 μm with the element concentration gradient gap. The isolated titanium peak lies in this layer.
Fig. 15  a Chip adhesion on the worn edge, b EDS spectrum of point A and c point B

Fig. 16  a WC particles in the chip and b EDS spectrum of point C

Fig. 17  a Worn edge, b magnified image of the worn edge, and c elements distribution in Line 1
The symmetrical section profile of the insert is shown in Fig. 18a. On the rounded edge, there is a crack through the edge tip. In the symmetrical section profile of the worn insert, a similar isolated CPS peak of Ti is also found in the scanning spectrum of Line 2 at nearly 30 μm from the flank face, as shown in Fig. 18b, indicating the same source of the titanium.

The semi-crater is filled with the material from chip adhesion, as the SEM image is shown in Fig. 19a. An EDS line scanning was made in the semi-crater profile to reveal the trace of chemical elements as shown in Fig. 19b. In the carbide side of the tool–chip interface, the content of W and Co is relatively low. A slightly higher amount of Ti is shown as well.

4 Discussion

4.1 Cutting force

Considering the same condition of tools and cutting parameters in the comparison test, the higher cutting force of M28 reveals the effect of the material property of M28 on its machinability. Figure 20 shows the metallographic image of the finished surface of M28. Due to the large grain size, the grain in the workpiece surface was cut in a transgranular way. It can be found that the remaining part of grains in the surface holds their boundaries with nearly no trace of grain deformation. The \( \alpha_2 \) precipitation plays a vital role in the strengthening of M28. As a consequence of thermodynamic instability associated with metastable \( \beta \) titanium alloys \([28]\), \( \alpha_2 \) precipitation obtained after aging treatments results strong resistance of \( \alpha/\beta \) interface to dislocation movement \([21]\). A mixture of coarse \( \alpha_2 \) and fine \( \alpha_2 \) causes inhomogeneous slip distribution \([4]\), as shown in Fig. 20. In addition, cold work generally enhances the aging response and leads to a more homogenous distribution of \( \alpha_2 \) \([29]\). All these effects result in a high cutting force.

4.2 Wear mechanism

In the cutting experiment of M28, two different tool wear modes were observed. As shown in Fig. 11a, serious edge chipping was found in the normal cutting speed, while flank wear as a continuous band was formed in high-speed cutting, as shown in Fig. 14a, b.
The edge chipping in the normal cutting speed is the result of the huge stress concentration at the edge tip and being accelerated by the $\alpha_s$ precipitation abrasion. The SEM image of the edge chipping area (Fig. 12a) and the piece of carbide material embedding in the chip (Fig. 13) indicates there was a brittle broken in the carbide tool. At a lower cutting temperature, the WC–Co carbide deforms in a brittle manner (lower than 700 °C) [30–32]. The resultant force of $F_x$ and $F_y$ at the cutting speed of 45 m/min is nearly 640 N in the experiment. However, considering the sharp geometry of the edge ($\gamma = -25^\circ$, $\alpha = 25^\circ$, as listed in Table 2) as well as the short chip–tool contact length (as reported to be in an order of magnitude of $\mu$m [33]) in titanium alloy cutting, the stress concentration at the edge is appreciable high. The maximum stress at the cutting edge of a 4 $\mu$m radius is estimated to be in an order of magnitude of GPa taking the reference from [34], which is much higher than the strength of WC–Co carbide (1600 ~ 2200 MPa, lower than 700 °C, as reported in [35]). Accordingly, edge chipping is expected. In addition, abrasive wear will be accelerated when the tool edge cuts in the coarse $\beta$ grain filled with the hardening phase $\alpha_s$, as shown in Fig. 20. The little cascading chip adhesion in the chipping area, as shown in Fig. 12b, indicates that the irregular edge formed in the fresh surface in the chipping took the place of the original cutting edge and proceeded cutting. Thus, edge chipping was aggravated and finally comes to a sudden break, as the development of VB is shown in Fig. 10.

In high-speed cutting, abrasive wear no longer dominates the wear mode due to the high temperature. As the
result of strong alternating thermal stress in the carbide during high-speed milling [25], the comb crack, as shown in Fig. 14b, indicates the cutting edge undergoes not only the concentration of stress but also the concentration of heat. The plastic deformation process of titanium alloy is subject to the competing mechanism among work hardening, strain rate hardening and thermal softening [36]. A large amount of plastic work, which is converted mostly into heat, is required in the cutting of M28 due to its ultra-high strength. β titanium alloys are much more sensitive to the thermal softening effect than α + β titanium alloys [37]. Hence, the α boosting effect will degrade as the thermal softening works with the increasing cutting temperature in high-speed cutting.

On the other side, the thermal conductivity of titanium alloy, i.e., Ti-6Al-4 V, ranges from 8–18 W/m °C [38, 39] while for WC–Co carbide it is 55 W/m °C [40]. Due to the gap in thermal conductivity, a large proportion (about 80%) [33] of the cutting heat in the titanium alloy cutting is conducted into the carbide tool. The plastic deformation of the edge (as shown in Fig. 17a) was the result of strength degradation of the carbide at high temperature. At a temperature higher than 600 °C, WC–Co carbide deforms mainly in ductile behavior [30–32], since the softening of Co (at around 600 °C) and WC (starts at around 900 °C) [41]. Hence, the high cutting temperature (as reported to be up to 850–1100 °C [33, 39, 42]) will lead to the reduction in the strength of carbide.

The mode of cutting-edge wear in the high-speed cutting of M28, as illustrated in Fig. 21, is an interactive process of mechanical load and chemical diffusion in the cutting.

In high-speed cutting of M28, under the high temperature and pressure, the chip adhered on the worn edge which was rounded from the original radius of 4 μm to more than 200 μm with a chip–tool contact length (archway length) of nearly 183 μm, as shown in Fig. 17. In the process, more chip–tool contact area was offered. The prerequisite of diffusion behavior was thus satisfied, namely: solid contact of chip and tool, the bilateral concentration gradient of the element on either side of the chip–tool interface, and enough active thermal energy [25, 43–45]. As the diffusion behavior was activated, W, Co, and C were found in the chip adhesion as shown in Fig. 15c due to the high reactivity of Ti. The scattered WC, as shown in Fig. 16a, was pulled out by the flowing chip due to the loss of binder in the carbide matrix. As the binder phase in the WC–Co carbide [46], once Co diffused out, the holding to the WC particles will be weakened and the loosened WC particles will be dropped out easily by the chip flow and carried away from the tool, leading to the formation of the crater in the rake face, as discussed in lots of research [15, 43, 47–51]. In the experiment, a semi-crater was formed at the tip of the cutting edge as Figs. 14c and 17b show. The enrichment of C and Ti in the chip–tool interface, as the EDS scanning of Line 3 shows (Fig. 19b), presents the trace of diffusion in the tiny area of the semi-crater.

Crater wear, as identified in the rake face, is usually reported and verified in the turning experiment, where the continuous chip contacts the flank face steadily, as illustrated in Fig. 22, while the semi-crater was formed in the rounded edge in a relatively smaller size (almost one order of magnitude smaller). As presented in Fig. 17b, the chip adhered at a tiny area in the cutting edge. Since the chip is formed slice by slice rather than a continuous way in milling, it can hardly contact the rake face. On the other side, in continuous cutting such as turning, almost no alternating stress affects the cutting edge. So the alternating stress in the edge of the milling tool should also be considered. A possible reason for the semi-crater formation is the combining interconnection of high-frequency impact in the cutting edge, carbide degradation at high temperature, and the diffusion wear. In high-speed milling of M28, the high temperature leads to the local thermal softening of the cutting edge. The high-frequency impact, as the instinct of high-speed milling, will generate alternating stress concentration locally in the tiny chip–tool contact area, leading to fatigue cracks of carbide [52]. Meanwhile, the titanium chip will adhere at the chip–tool contact area and fill the fracture crack. The high reactivity of titanium and the high temperature promote chemical diffusion, which also causes the decomposition of the carbide; thus, the crater will gradually be formed. Due to the low thermal conductivity of titanium alloy and the high spindle rotation, the chip adhesion and edge do not have enough time to conduct out the heat during the time gap from cut-out to next cut-in. Hence, the tool edge can hold the cutting heat through the interrupted cutting process and the thermal-activated diffusion is maintained.

In addition, the kinetically driven decarburization of carbide will occur at a high temperature according to the following reactions [53]:

\[ 2WC \rightarrow W_2C + C \]  \hspace{1cm} (2)

\[ W_2C \rightarrow 2W + C \]  \hspace{1cm} (3)

Such dissociation of WC in the carbide will promote the formation of the RC layer of the tool as shown in Fig. 17c. The variation in the carbon content of tungsten carbide can alter the phase composition and affects the carbide properties [54]. With the enrichment of C in the superficial layer, additional graphite and the \( \eta \)-phase will emerge and lead to a substantial drop in hardness and wear resistance of the carbide due to the negligible strength of graphite [54–57]. The crack in the edge tip, as shown in Fig. 18, indicates the strength degradation of carbide. In the diffusion layer, as shown in Fig. 17c, the overlapped CPS peaks of Ti and C

 Springer
spectra indicate the compound of Ti and C. The diffused C from the carbide can easily combine with the Ti following the reaction in Eqs. (4) and (5) [58]

\[ WC + Ti = W + TiC \]  

(4)

\[ Ti + C = TiC \]  

(5)

TiC works as a boundary inhibiting further chemical element diffusion [58–60]. However, considering the continuous chip flow, the possibility that TiC might be rushed by the chip flow in the dynamic cutting process should not be discounted.

The trace of titanium was detected near the chip–tool interface of the carbide as the result of diffuson wear in lots of research [15, 43, 48, 61]. However, the Ti element distribution in the worn edge as presented in Fig. 17c needs more discussion. Since K40 carbide contains only WC and Co, the titanium in the chip flow should be transferred into the carbide matrix to form an isolated Ti peak. The diffusion behavior presents the concentration gradient of elements (Ti, Wo, Co, etc.) rather than an isolated enrichment. The isolated Ti peak inside the WC–Co carbide matrix requires straight access for the titanium transformation. A possible explanation is it’s the comb crack (as shown in Fig. 14b) that offered the straight access while the huge pressure in the chip–tool contact zone propelled the flowing titanium chip into the inner carbide matrix, while the crack in the section profile, as shown in Fig. 18a, retained some titanium chip material.

5 Conclusions

Machinability of the novel metastable \( \beta \) titanium alloy M28 (Ti-4Al-5Mo-5 V-6Cr-1Nb) is evaluated in the experiment from the view of cutting force and tool wear in this paper. Conclusions can be drawn as follows:

1. The machinability of M28 is poor considering the high cutting force and considerably short tool life. The “trans-granular cutting” resulting from the coarse grain size in metallographic structure combing the aging-hardening effect leads to the high cutting force.
2. Serious edge chipping in the flank face occurs in the milling of M28 at a normal cutting speed \( (v_c=45 \text{ m/min}) \) as a result of the huge stress concentration at the edge and being accelerated by secondary \( \alpha \) phase abrasion.
3. Chip adhesion, comb cracks, and tool plastic deformation were found in the high-speed cutting of M28. High cutting temperature promotes the transformation of the tool wear mode. WC grains were extracted by the chip due to the Co diffusion. The semi-crater at the edge tip is formed by the interaction of high-frequency impact, carbide thermal softening, and element diffusion.
4. A rich carbon layer is formed at the superficial of the tool edge in high-speed cutting. The enrichment of carbon leads to the carbide strength degradation; thus, the inner crack was formed. An isolated Ti enrichment was found inside the carbide. Comb cracks at the flank face offered the access for titanium chip to move into the tool.
5. Considering the wear mode of milling M28, reducing the cutting temperature is a possible approach to increase the tool life.

Acknowledgements This work is sponsored by the National Natural Science Foundation of China (No. 52075251).

Authors’ contributions All authors contributed to the study conception and design. Material preparation was performed by Hui Tian and Jia Yin. Experiment design was performed by Yifan Jiang with the guidance from Hui Tian, Jia Yin, and Yinfei Yang. Experiment work, data collection, and analysis were performed by Yifan Jiang with the guidance from Liang Li and Guolong Zhao. The first draft of the manuscript was written by Yifan Jiang, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work is sponsored by the National Natural Science Foundation of China (No. 52075251).

Availability of data and material Not applicable. Code availability Not applicable.

Code availability Not applicable.
Declarations

Ethics approval Not applicable.
Consent to participate Not applicable.
Consent for publication Not applicable.
Conflicts of interest/competing interests The authors have no relevant financial or non-financial interests to disclose.

References

1. Zs ZHU (2013) Research and development of new-brand titanium alloys of high performance for aeronautical applications (in Chinese). Aviation Industry Press, Beijing
2. Chen W, LIU YX, LI ZQ (2020) Research status and development trend of high-strength β titanium alloys (in Chinese). J Aeronaut Mater 40(03):63–76
3. Cotton JD, Briggs RD, Boyer RR, Tamirisakandala S, Rasso P, Shchetinok N, Fanning JC (2015) State of the art in beta titanium alloys for airframe applications. JOM 67(6):1281–1303. https://doi.org/10.1007/s11837-015-1442-4
4. Leyens C, Peters M (2003) Titanium and titanium alloys. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim https://doi.org/10.1002/3527602119.ch2
5. Yumak N, Aslantaş K (2020) A review on heat treatment efficiency in metastable β titanium alloys: the role of treatment process and parameters. J Mater Res Technol 9(6):15360–15380. https://doi.org/10.1016/j.jmrt.2020.10.088
6. Singh P, Pungotra H, Kalsi NS (2017) On the characteristics of titanium alloys for the aircraft applications. Mater Today Proc 4(8):8971–8982. https://doi.org/10.1016/j.matpr.2017.07.249
7. Machai C, Biermann D (2011) Machining of β-titanium-alloy Ti–10V–2Fe–3Al under cryogenic conditions: Cooling with carbon dioxide snow. J Mater Process Technol 211(6):1175–1183. https://doi.org/10.1016/j.jmatprotec.2011.01.022
8. Zlatin N, Field M (1973) Procedures and precautions in machining titanium alloys. In: Jaffe RI, Burte HM, editors. Titanium Science and Technology. Springer US, Boston, MA https://doi.org/10.1007/978-1-4757-1346-6_37
9. Machai C, Biermann D (2011) Machining of a hollow shaft made of β-titanium Ti–10V–2Fe–3Al. IEEE Int Symp Assem Manuf 1–6. https://doi.org/10.1109/ISAM.2011.5942364
10. Arrazola PJ, Garay A, Iriarte LM, Armendia M, Marya S, Le Maître F (2009) Machinability of titanium alloys (Ti6Al4V and Ti5553.3). J Mater Process Technol 209(5):2223–2230. https://doi.org/10.1016/j.jmatprotec.2008.06.020
11. Ezugwu EO (2004) High speed machining of aero-engine alloys. J Braz Soc Mech Sci Eng 26:1–11. https://doi.org/10.1590/S1678-58782004000100001
12. Machai C, Iqbal A, Biermann D, Upmeier T, Schumann S (2013) On the effects of cutting speed and cooling methodologies in grooving operation of various tempers of β-titanium alloy. J Mater Process Technol 213(7):1027–1037. https://doi.org/10.1016/j.jmatprotec.2013.01.021
13. Rahman Rashid RA, Sun S, Wang G, Dargusch MS (2011) Machinability of a near beta titanium alloy. Proc Inst Mech Eng Part B J Eng Manuf 225(12):2151–2162. https://doi.org/10.1177/0954406211406649
14. Sun Y, Huang B, Puleo DA, Jawahir IS (2015) Enhanced machinability of Ti-5553 alloy from cryogenic machining: Comparison with MQL and fluid-cooled machining and modeling. Procedia CIRP 31:477–482. https://doi.org/10.1016/j.procir.2015.03.099
15. Bai D, Sun J, Chen W, Wang T (2017) Wear mechanisms of WC/Co tools when machining high-strength titanium alloy TB6 (Ti-10V-2Fe-3Al). Int J Adv Manuf Technol 90(9):2863–2874. https://doi.org/10.1007/s00170-016-9607-z
16. Ikuta A, Shinozaki K, Masuda H, Yamane Y, Kuroki H, Fukaya Y (2002) Consideration of the adhesion mechanism of Ti alloys using a cemented carbide tool during the cutting process. J Mater Process Technol 127(2):251–255. https://doi.org/10.1016/S0924-0136(02)00152-8
17. Tasciglio E, Ghairibi A, Kaynak Y (2019) High speed machining of near-beta titanium Ti-5553 alloy under various cooling and lubrication conditions. Int J Adv Manuf Technol 102(9):4257–4271. https://doi.org/10.1007/s00170-019-03291-3
18. Pimenov DY, Mia M, Gupta MK, Machado AR, Tomaz IV, Sarikaya M, Wojciechowsk S, Mikolajczyk T, Kaplonek W (2021) Improvement of machinability of Ti and its alloys using cooling-lubrication techniques: a review and future prospect. J Mater Res Technol 11:719–753. https://doi.org/10.1016/j.jmrt.2021.01.031
19. Mouritz AP (2012) Introduction to aerospace materials. Woodhead Publishing, UK https://doi.org/10.1533/9780857095152.020
20. Nguyen T, Park K-H, Wang X, Olortegui-Yume J, Wong T, Schrook D, Kim W, Kwon P, Kramer B (2015) The genesis of tool wear in machining, ASME Int Mech Eng Congress Expo. https://doi.org/10.1115/IMECE2015-52531
21. Huang S, Zhao Q, Wu C, Lin C, Zhao Y, Jia W, Mao C (2021) Effects of β-stabilizer elements on microstructure formation and mechanical properties of titanium alloys. J Alloys Compd 876:160085. https://doi.org/10.1016/j.jallcom.2021.160085
22. Siddu SS, Singh H, Gpereel MAH (2021) A review on alloy design, biological response, and strengthening of β-titanium alloys as biomaterials. Mater Sci Eng C 121:116161. https://doi.org/10.1016/j.msec.2020.111661
23. Bania PJ (1994) Beta titanium alloys and their role in the titanium industry. JOM 46(7):16–19. https://doi.org/10.1007/BF03220742
24. Yu P-J, Hsu Y-Y, Wang S-H, Yang J-R, Yang Y-L, Chang H-Y, Chen C-Y, Chen H-R (2020) Comparison of dynamic-aging creep and pre-aged creep in Ti-15–3 beta titanium alloy. Mater Sci Eng A 798:140135. https://doi.org/10.1016/j.msea.2020.140135
25. Klocke F (2011) Manufacturing processes 1: Cutting. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-11979-8
26. Abele E, Hasenfratz C, Bücker M (2017) Modeling of process forces with respect to technology parameters and tool wear in milling Ti6Al4V. Prod Eng 11(3):285–294. https://doi.org/10.1016/s11740-017-0739-2
27. Komanduri R (1982) Some clarifications on the mechanics of chip formation when machining titanium alloys. Wear 76(1):15–34. https://doi.org/10.1016/0044-1688(82)90113-2
28. Vishnu J, Sankar M, Rack HJ, Rao N, Singh AK, Manivasagam G (2020) Effect of phase transformations during aging on tensile strength and ductility of metastable beta titanium alloy Ti–35Nb–7Zr–5Ta-0.35O for orthopedic applications. Mater Sci Eng A 779:139127. https://doi.org/10.1016/j.msea.2020.139127
29. Ankem S, Seagle S (1984) Heat treatment of metastable beta titanium alloys. In: Boyer RRRH (ed) Beta Titanium Alloys in the 80’s. TMS, USA, pp. 107–126
30. Emani SV, Ramos dos Santos AFC, Shaw LL, Chen Z (2016) Investigation of microstructure and mechanical properties at low and high temperatures of WC–6wt% Co. Int J Refract Metals Hard Mater 58:172–181. https://doi.org/10.1016/j.ijrmhm.2016.04.009
31. Buss K, Mari D (2004) High temperature deformation mechanisms in cemented carbides and cermets studied by mechanical spectroscopy. Mater Sci Eng A 370(1):163–167. https://doi.org/10.1016/j.msea.2002.12.004
32. Milman YV, Luyckx S, Goncharuck VA, Northrop JT (2002) Results from bending tests on submicron and micron WC–Co grades at elevated temperatures. Int J Refract Metals Hard Mater 20(1):71–79. https://doi.org/10.1016/S0263-4386(01)00072-5

33. Ezugwu EO, Wang ZM (1997) Titanium alloys and their machinability—a review. J Mater Process Technol 68(3):262–274. https://doi.org/10.1016/S0924-0136(96)00303-1

34. Bouzakis KD, Bouzakis E, Kombogianniss S, Makrimallakis S, Skordaris G, Michailidis N, Charalampous P, Paraskevopoulos R, M’Saoubi R, Aurich JC, Barthelmä F, Biermann D, Denkena B, Dimitrov D, Engin S, Karpuschewski B, Klocke F, Özel T, Poulachon G, Rech J, Schulze V, Settineri L, Sivastava A, Wegener K, Uhlmann E, Zeman P (2014) Effect of cutting edge preparation of coated tools on their performance in milling various materials. CIRP J Manuf Sci Technol 7(3):264–273. https://doi.org/10.1016/j.cirp.2014.05.003

35. Kindermann P, Schlund P, Sockel HG, Herr M, Heinrich W, Göttig K, Schleinkofer U (1999) High-temperature fatigue of cemented carbides under cyclic loads. Int J Refract Metals Hard Mater 17(1):55–68. https://doi.org/10.1016/S0263-4386(99)00014-1

36. Wright TW (2002) The physics and mathematics of adiabatic shear bands. Cambridge University Press, UK

37. Shivpuri R, Hua J, Mittal P, Sivastava AK, Lahoti D (2002) Microstructure-mechanics interactions in model chip segmentation during titanium machining. CIRP Ann 51(1):71–74. https://doi.org/10.1016/S0007-8506(07)61648-1

38. Abdel-Aal HA, Nouari M, El Mansori M (2009) Influence of thermal conductivity on wear when machining titanium alloys. Tribol Int 42(2):359–372. https://doi.org/10.1016/j.triboint.2008.07.005

39. Ginting A, Nouari M (2006) Experimental and numerical studies on the performance of alloyed carbide tool in dry milling of aerospace material. Int J Mach Tools Manuf 46(7):758–768. https://doi.org/10.1016/j.ijmachtools.2005.07.035

40. Özel T, Sima M, Sivastava AK, Kaftanoglu B (2010) Investigations on the effects of multi-layered coated inserts in machining Ti–6Al–4V alloy with experiments and finite element simulations. CIRP Ann 59(1):77–82. https://doi.org/10.1016/j.cirp.2010.03.055

41. Mari D, Bolognini S, Feusier G, Viatte T, Benoit W (1999) Experimental study to investigate the mechanical behaviour of hardmetals for cutting tools. Int J Refract Metals Hard Mater 17(1):209–225. https://doi.org/10.1016/S0263-4386(98)00078-X

42. Armendía M, Garay A, Iriarte LM, Arrazola PJ (2010) Comparison of the machinabilities of Ti6Al4V and TIMETAL® 54M using uncoated WC–Co tools. J Mater Process Technol 210(2):197–203. https://doi.org/10.1016/j.jmatprot.2009.08.026

43. Zhang S, Li JF, Deng JX, Li YS (2008) Investigation on diffusion wear during high-speed machining Ti-6Al-4V alloy with straight tungsten carbide tools. Int J Adv Manuf Technol 44(1):17–25. https://doi.org/10.1007/s00170-008-1803-z

44. Wong T, Kim W, Kwon P (2004) Experimental support for a model-based prediction of tool wear. Wear 257(7):790–798. https://doi.org/10.1016/j.wear.2004.03.010

45. Min W, Min W, Youzen Z (1988) Diffusion wear in milling titanium alloys. Mater Sci Technol 4(6):548–553. https://doi.org/10.1179/mst.1988.4.6.548

46. Krakhmalev PV, Adeva Rodil T, Bergström J (2007) Influence of microstructure on the abrasive edge wear of WC–Co hardmetals. Wear 263(1):240–245. https://doi.org/10.1016/j.wear.2006.10.019

47. Bai D, Sun J, Chen W, Du D (2016) Molecular dynamics simulation of the diffusion behaviour between Co and Ti and its effect on the wear of WC/Co tools when titanium alloy is machined. Ceram Int 42(15):17754–17763. https://doi.org/10.1016/j.ceramint.2016.08.103

48. Graves A, Norgren S, Wan W, Singh S, Kritikos M, Xiao C, Crawford P, Jackson M (2021) On the mechanism of crater wear in a high strength metastable β titanium alloy. Wear 484–485:203998. https://doi.org/10.1016/j.wear.2021.203998

49. Odelro S, Kaplan B, Kritikos M, Johansson M, Norgren S (2017) Experimental and theoretical study of the microscopic crater wear mechanism in titanium machining. Wear 376–377:115–124. https://doi.org/10.1016/j.wear.2017.01.10

50. Bai DS, Sun JF, Wang K, Chen WY (2018) Diffusion behavior and wear mechanism of WC/Co tools when machining of titanium alloy. Solid State Phenomena 279:60–66. https://doi.org/10.4028/www.scientific.net/SSP.279.60

51. Kaplan B, Odelro S, Kritikos M, Bejiani R, Norgren S (2018) Study of tool wear and chemical interaction during machining of Ti6Al4V. Int J Refract Metals Hard Mater 72:253–256. https://doi.org/10.1016/j.ijrmhm.2017.12.012

52. Roa JJ, Simson S, Grasso J, Arcidiacono M, Escalada L, Soldera F, García J, Sosa AD (2020) Cyclic contact fatigue of cemented carbides under dry and wet conditions: Correlation between microstructure, damage and electrochemical behavior. Int J Refract Metals Hard Mater 92:105279. https://doi.org/10.1016/j.ijrmhm.2020.105279

53. Nerz J, Kushner B, Rotoilco A (1992) Microstructural evaluation of tungsten carbide-cobalt coatings. J Therm Spray Technol 1(2):147–152. https://doi.org/10.1007/BF02659015

54. Kreimer GS, Vakhovskaya MR (1965) The effect of carbon content on the mechanical properties of tungsten carbide-cobalt hard alloys. Soviet Powder Metall and Ceram 4(6):454–459. https://doi.org/10.1016/0007-2573(65)90156-5

55. Zhang ML, Zhu SG, Zhu SX (2006) Carbon content change and its influence on structure and properties of ultrafine and nanocemented carbide (in Chinese). Mater Rep 08:65–68

56. Bondarenko VP, Pavlotskaya EG (1997) Hydrogen-containing chemically active gas medium for controlling carbon content of tungsten-base hard alloys. Int J HydroG Energy 22(2):205–212. https://doi.org/10.1016/S0360-3199(96)00156-5

57. Hoff T, Larsson H, Giuliani F, Crawford P, Wynne B, Jackson M (2016) Predicting chemical wear in machining titanium alloys via a novel low cost diffusion couple method. Procedia CIRP 45:219–222. https://doi.org/10.1016/j.procir.2016.01.196

58. Hartung PD, Kramer BM, von Turkovich BF (1982) Tool wear in titanium machining. CIRP Ann 31(1):75–80. https://doi.org/10.1016/S0007-8506(07)63272-7

59. Hoff T, Crawford P, Jackson M (2017) On the mechanism of tool crater wear during titanium alloy machining. Wear 374–375:15–20. https://doi.org/10.1016/j.wear.2016.12.036

60. Ramirez C, Idhil Ismail A, Gendarme C, Dehmas M, Aeby-Gautier E, Poulachon G, Rossi F (2017) Understanding the diffusion wear mechanisms of WC-10%Co carbide tools during dry machining of titanium alloys. Wear 390–391:61–70. https://doi.org/10.1016/j.wear.2017.07.003

61. Jianxin D, Yousheng L, Wenlong S (2008) Diffusion wear in dry cutting of Ti–6Al–4V with WC/Co carbide tools. Wear 265(11):1776–1783. https://doi.org/10.1016/j.wear.2008.04.024

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.