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ORIGINAL ARTICLE

Influence of cutting speed on cutting force, flank temperature, and tool wear in end milling of Ti-6Al-4V alloy

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Abstract Tool wear is one of the most important problems in cutting titanium alloys due to the high-cutting temperature and strong adhesion. Recently, the high-speed machining process has become a topic of great interest for titanium alloys, not only because it increases material removal rates, but also because it can positively influence the properties of finished workpiece. However, the process may result in the increase of cutting force and cutting temperature which will accelerate tool wear. In this paper, end milling experiments of Ti-6Al-4V alloy were conducted at high speeds using both uncoated and coated carbide tools. The obtained results show that the cutting force increases significantly at higher cutting speed whether the cutter is uncoated carbide or TiN/TiAlN physical vapor deposition (PVD)-coated carbide. For uncoated carbide tools, the mean flank temperature is almost constant at higher cutting speed, and no obvious abrasion wear or fatigue can be observed. However, for TiN/TiAlN PVD-coated carbide tools, the mean flank temperature always increases as the increase of cutting speed, and serious abrasion wear can be observed. In conclusion, the cutting performance of uncoated inserts is relatively better than TiN/TiAlN PVD-coated inserts at a higher cutting speed.

Keywords End milling · Titanium alloy · Cutting force · Cutting temperature · Tool wear

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1 Introduction

Application of titanium alloys has increased in many fields in the past 50 years, especially in the aerospace [1, 2], automotive [3, 4], and biomedical industries [5, 6]. Because titanium alloys have excellent properties such as high strength/weight ratio, strong corrosion resistance, and good biocompatibility [7–9]. However, titanium alloys are regarded as difficult-to-cut materials because of their low-thermal conductivity, high-chemical reactivity, and low modulus of elasticity [10]. These material properties can cause high-cutting temperature in cutting zone and strong adhesion between the tool and workpiece material. Hence, tool wear is intense in the machining of titanium alloys. Though coolants can be used to reduce cutting temperature and cutting force [11], dry cutting is desirable as it can offer cost reduction and atmosphere of non-pollution. For example, Ribeiro et al. [12] pointed out that dry environment was suitable for the selected process parameters in turning titanium alloy Ti-6Al-4V. In addition, high-speed machining has been applied for increasing the productivity and improving the machined surface quality for a long time [13–15], but the high-speed application on difficult-to-cut materials (such as titanium alloys) is still relatively new. Siekmann [16] pointed out that "machining of titanium and its alloys would always be a problem, no matter what techniques are employed to transform this metal into chips." So, the poor machinability of titanium alloys attracts many researchers to explore new methods for minimizing tool wear and machining cost [17].

As for the machining of titanium alloys, cutting temperature and cutting force are extremely important, which can influence the tool performance, machined surface integrity, and chip morphologies. Thus, it is necessary to analyze the variation of cutting temperature and cutting force under different conditions. In this research field, some special machining methods were used to cut titanium alloys. For instance, Bermingham et al. [18] investigated the tool life and wear mechanisms during thermally assisted machining (TAM) Ti-6Al-4V alloy. The results showed that TAM did not significantly improve tool life. Rashid et al. [19] introduced the behavior of the Ti-6Cr-5Mo-5V-4Al beta titanium alloy using laser-assisted machining (LAM). This investigation showed that LAM significantly reduced the cutting force within a certain range of cutting parameters. For the variation of cutting force, Niu et al. [20] presented that the resultant cutting force increased with increasing cutting speed in the process of face milling TC6 alloy. Significantly, it was obvious when the cutting speed was changed from 80 to 140 m/min. Shi et al. [21] assessed the machining performance of WK10 carbide by cutting titanium alloy TC21. They concluded that the three cutting forces (feed force, thrust force, main cutting force) increased with the increase of cutting speed. However, some researchers obtained different results. For instance, Huang et al. [22] presented that the maximum cutting force increased first and then decreased with increasing cutting speed due to the effect of strain hardening and thermal softening of the workpiece materials. Wang et al. [23] analyzed the performance of binderless CBN tools in the high-speed milling of Ti-6Al-4V alloy. They proposed that the increase of cutting speed led to the decrease of the average resultant force. Additionally, Sun et al. [24] examined the process of dry-turning Ti-6Al-4V alloy. They also pointed out that the cutting force reduced dramatically when the cutting speed was higher than 113 m/min because of the thermal softening of workpiece materials.

To evaluate the variation of cutting temperature, Li et al. [25] investigated the high-speed milling of Ti-6Al-4V using uncoated K10 carbide. They proposed a method to measure cutting temperature. Based on the measurement of cutting temperature, the effect of cutting speed on the cutting temperature was investigated. The results showed that cutting temperature increased with cutting speed, and no reduction of cutting temperature at higher cutting speed was observed. Same results were obtained from studies of the tool face temperature which changed with cutting speed in the machining of Ti-6Al-4V [26, 27]. Additionally, Hood et al. [28] found that the cutting temperature almost increased linearly with a similar rise of cutting speed in cutting γ-TiAl alloy. However, some results were not exactly same as the former. For example, Muller et al. [29] measured the temperature using two-color pyrometer FIRE-1 in high-speed external turning Ti-6Al-4V alloy. The results showed that measured temperatures were a broad distribution and could not reach a steady state value due to the strong influence of the flank wear. Rao et al. [30] used FEM to simulate the variation of average temperature in face milling of Ti-6Al-4V. The average temperature in the primary deformation zone showed a nearly flat trend with increasing cutting speed. The average temperature values remained nearly constant when the speed was changed from 121.9 to 182.9 m/min.

From the above analysis, the high-speed machining process of titanium alloys is very complicated. Some results obtained by researchers are inconsistent, such as the variation of cutting temperature and cutting force with the increase of cutting speed. The objective of this study is to determine the influence of cutting speed on the cutting temperature and cutting force and to provide comparison results between uncoated and coated tools. In this paper, the mean flank temperature was measured by high-speed infrared pyrometer and the cutting force was measured by dynamometer. Based on the experimental observations, the effect of cutting speed on flank temperature and cutting force was analyzed and the cutting performance of uncoated and TiN/TiAlN physical vapor deposition (PVD)-coated tools was evaluated. Such information is useful and helpful to understand and enhance the machinability of titanium alloys.

Table 2 Mechanical properties of the titanium alloy Ti-6Al-4V

Properties,	Value
Density (kg/m^3)	4,430
Hardness (HRC)	36
Elastic modulus (GPa)	114
Poisson' ratio	0.33
Melting temperature (°C)	1,668
Thermal conductivity (W/m·K)	6.7
Yield strength (MPa)	834
Tensile strength (MPa)	932
Reduction in area (%)	36
Elongation (%)	14

Table 1 Chemical composition of the titanium alloy Ti-6Al-4V

Elements	Al	V	Fe	Si	C	N	H	O	Ti
Wt. (%)	5.5–6.8	3.5–4.5	0.3	0.1	0.1	0.05	0.015	0.2	Balance

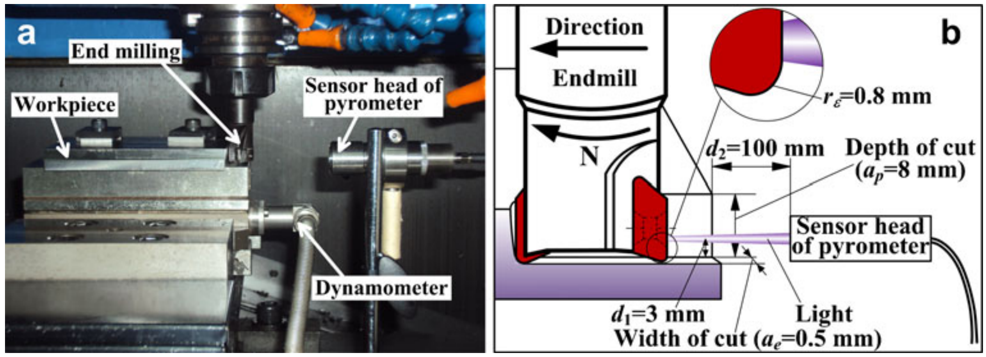

Fig. 1 The experiment set-up of end milling titanium alloy Ti-6Al-4V

2 Experimental procedures

2.1 Workpiece and tool materials

The material employed in our experiments was a commercial titanium alloy Ti-6Al-4V which was known to be the promising materials for the application of aerospace and medical implants. Its chemical composition is given in Table 1 [31], while Table 2 lists the mechanical properties of investigated material [32]. Dimensions of the workpiece were 132.7×67.3×15.5 mm. Uncoated carbide inserts (SECO XOMX090308TR-ME06 H25) and TiN/TiAlN PVD coated carbide inserts (SECO XOMX090308TR-ME06 F40M) were mounted onto a tool holder of type R217.69-2020.0-10-2A, respectively, and then used to cut the titanium alloy Ti-6Al-4V. The tool holder has two inserts, and milling diameter is 20 mm. The geometry of coated and uncoated inserts is identical. The insert is a rhombic shape end milling insert with a cutting edge length of 10.8 mm, a width of 6.35 mm, a thickness of 3.65 mm, a 0.8-mm corner radius, a 24 ° rake angle, a 11 ° clearance angle, and a 90 ° side-cutting edge angle. And they have the same edge radius.

2.2 Machining tests

Milling is an intermittent cutting process, as their cutting edges repeatedly enter and exit the workpiece. Usually, down milling is recommended in production for a longer tool life and better surface quality. Therefore, the down milling was selected in our experiment. Figure 1 shows the experiment set-up of end milling of titanium alloy Ti-6Al-4V. Titanium alloy workpiece was milled by computer numerical control (CNC) milling machine (Mazak FJV-250). Spindle speed and feeding speed are common parameters in the practical production for facilitating operation. In this experiment, they were changed from 2,000 to 10,000 rpm and 200 to 1,000 mm/min, respectively. The major experimental parameters are shown in Table 3. Kistler 9527B dynamometer was used to measure cutting force and DEWE software was used to record the values of cutting force. Non-contact infrared pyrometer KLEIBER 730-LO with optics fiber was used to measure the mean flank temperature and the Labview software was used to record the values of temperature, as shown in Fig. 1a. The sensor head model of pyrometer is LVA 25. The distance between sensor head and target object can change from 110 to 800 mm and the corresponding spot size of the probe beam changes from 0.8 to 5 mm. The data acquisition and processing time of pyrometer is 180 µs. The emissivity is adjustable between 0.1 and 1. The signal processing unit of the pyrometer provides a standard signal from 4 to 20 mA which correspond to 300 and 2,300 °C, respectively. Incidentally, mean flank temperature is the mean temperature in a zone of the tool flank face close to cutter edge. The zone is corresponding to the minimum spot (diameter=0.8 mm) of the probe beam of pyrometer. The temperature is slightly lower than actual value, because the insert is cooled in air after the cutting engagement.

In the experiment, the sensor head was perpendicular to the spindle axis of the end mill, as seen in Fig. 1b. The distance d_1 between the measurement spot and tool tip was 3 mm (the cutter corner radius r_ε is 0.8 mm. A distance d_1 that is bigger than 1 mm is appropriate for obtaining a circular spot). The distance d_2 between sensor head and workpiece was 100 mm. The width of cut a_e was 0.5 mm and the depth of cut a_p was 8 mm. In the end milling of the titanium alloy, the workpiece was fixed and the cutter was moved ahead. The used inserts were replaced with new inserts after each cutting operation for observing the tool wear. After the end milling test, the surface

Table 3 Experimental parameters of end milling Ti-6Al-4V alloy

Matching parameters	Value
Cutting speed (v_c)	62.8–628 m/min
Feed rate (f_z)	0.05 mm/tooth
Depth of cut (a_p)	8 mm
Width of cut (a_e)	0.5 mm
Cooling and lubrication	Dry

of tool inserts was etched in 2 % HNO_3+3 % HF+95 % H_2O, and then a scanning electron microscope (SEM-JEOL Model No. 5600LV) was used to investigate the tool wear.

2.3 Emissivity of tool materials

The emissivity of an object is the most important value when determining its temperature with a pyrometer [33]. The emissivity is dependent on the composition of the material and its temperature. Therefore, an experiment was performed for measuring the emissivity of the cutter. Figure 2 shows the experiment set-up for measuring the emissivity of the milling cutter. In this experiment, the cutter was put in the electric furnace (CWF 1200 Carbolite). A K-type thermocouple was used to calibrate the emissivity of milling cutter in different temperatures. The values of thermocouple were recorded by Yokogawa XL100 data logger. Thermocouple and pyrometer measured the temperature of the cutter simultaneously. Subsequently, the emissivity would be obtained when the temperature measured by pyrometer was equal to the temperature measured by thermocouple. Table 4 shows the emissivity of uncoated carbide inserts when the temperature changes from 327.8 to 709.1ºC. And the emissivity of TiN/TiAlN PVD-coated carbide insert was also investigated when the temperature was close to 400ºC.

3 Results and discussion

3.1 Analysis of cutting force

The study of cutting force is critically important in machining operations, because cutting force co-relate strongly with cutting performance, such as surface accuracy, tool wear and cutting temperature, etc. [13]. In our experiment, the maximum values of resultant cutting force were investigated in end milling. Figure 3 shows the resultant cutting force at different cutting speeds. It can be observed that the resultant cutting force produced by TiN/TiAlN PVD-coated carbide is higher than that produced by uncoated carbide. When the cutting speed (v_c) is lower than 125.6 m/min, the resultant cutting forces almost behave to be a constant whether the cutter is uncoated carbide or TiN/TiAlN PVD-coated carbide. Generally, the workpiece material is subjected to the effect of strain hardening and thermal softening in the machining of titanium alloy, especially at high temperature [34, 35]. The cutting force almost behaves to be a constant when the cutting speed is changed from 62.8 to 125.6 m/min, because the effect of strain hardening is equivalent to thermal softening. However, it increases significantly when the cutting speed is higher than 125.6 m/min. This is because the higher cutting force is required when the effect of strain hardening predominates over the effect of thermal softening. Similar results were also obtained by Shi et al. [21].

It also can be noted from Fig. 3 that the cutting force decreases when the cutting speed is 376.8 m/min in the milling process of titanium alloy using TiN/TiAlN PVD-coated inserts. In general, the cutting force decreases with the increase of cutting speed due to thermal softening and chip thickness reduction [36]. Therefore, it is possible that the cutting force decreases when the cutting speed is 376.8 m/min since the effect of thermal softening and chip thickness reducing predominates over the effect of strain hardening. Similar results were also reported by Huang et al. [22]. In our experiment, the phenomenon of chip ignition could be

Table 4 Emissivity of uncoated carbide and coated carbide inserts at different temperatures

Material	Emissivity	Pyrometer temperature (°C)	Thermocouple temperature (°C)	Furnace temperature (°C)
Uncoated carbide	0.73	327.8	327.8	345
	0.73	431.3	435.9	445
	0.83	513.3	512.5	520
	0.87	604.8	603.6	610
	0.91	710.9	709.1	710
TiN/TiAlN PVD-coated carbide	0.73	396.6	389.8	400

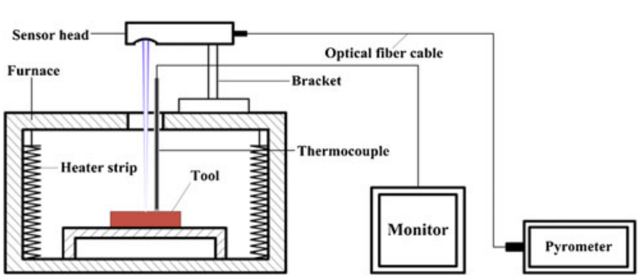

Fig. 2 Experiment set-up for measuring the emissivity of milling cutter

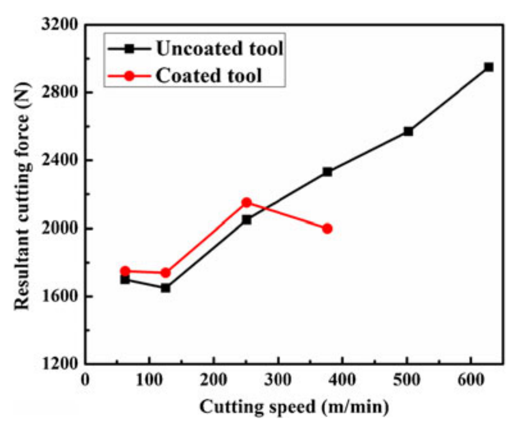

Fig. 3 Effect of cutting speed on the resultant cutting force

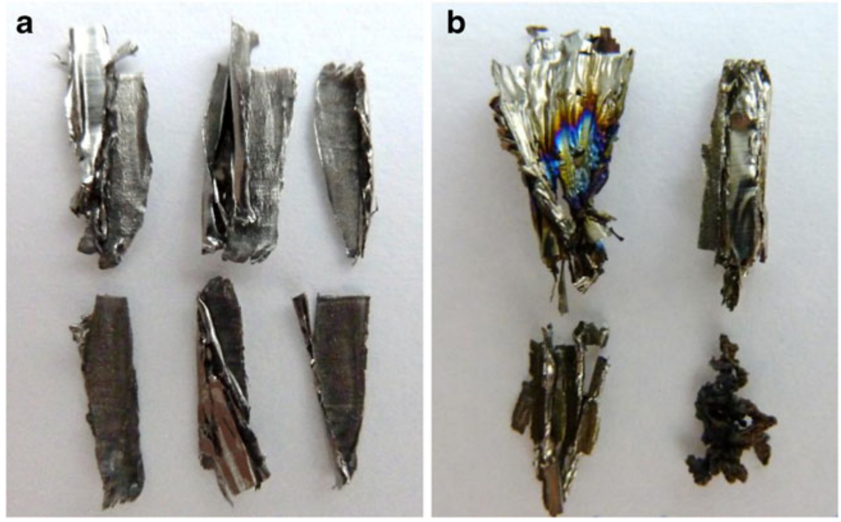

Fig. 4 Characteristics of chips produced at a cutting speed of 376.8 m/min. **a** The cutters are uncoated carbide inserts. **b** The cutters are TiN/TiAlN PVD-coated carbide inserts

observed at the cutting speed of 376.8 m/min. As shown in Fig. 4a, b, the characteristics of chips produced by uncoated carbide tools and TiN/TiAlN PVD-coated carbide tools are compared when the cutting speed is 376.8 m/min. Obviously, the burning residues of chips can be seen for TiN/TiAlN PVD-coated tools. Similar phenomenon of chip ignition was also reported by Li et al. [32]. Incidentally, the milling experiments of coated insert were not performed for the cutting speed higher than 376.8 m/min, considering the safety of sensor head and CNC milling machine.

3.2 Analysis of cutting temperature

The increase of cutting temperature is due to the heat energy generated in cutting and accumulated in the cutting region. High-cutting temperature is an important reason for the rapid tool wear in the machining of titanium alloys. Usually, the rake face temperature is difficult to be measured in the milling process, because the cutter rotates with a high speed. Consequently, mean flank temperature was investigated by infrared pyrometer in the study. Figure 5 shows the relationship between the mean flank temperature and the time of cutting when the cutting speed is 628 m/min. According to the previous analysis, the maximum value of temperature on the flank face close to cutter edge can be obtained when the distance d_2 between flank face and sensor head is 110 mm. And the diameter of the measurement spot is 0.8 mm.

From the previous results (see Table 4), the pyrometer needs to be adjusted before each milling experiment to set the tool emissivity in order to obtain the actual temperature on flank face. Table 5 shows the emissivity of uncoated and coated tools at different cutting speeds.

After milling, the variation of mean flank temperature vs. cutting speed in end milling of Ti-6Al-4V alloy was analyzed. As shown in Fig. 6, the mean flank temperature of TiN/TiAlN PVD-coated tools is higher than uncoated tools. And the mean flank temperature increases significantly when the cutting speed is changed from 62.8 to 376.8 m/min. This may be due to the low-thermal conductivity of TiN/TiAlN PVD-coated tools. As for the uncoated carbide tools, the mean flank temperature increases when the cutting speed is lower than 125.6 m/min, however, it remains nearly constant (about

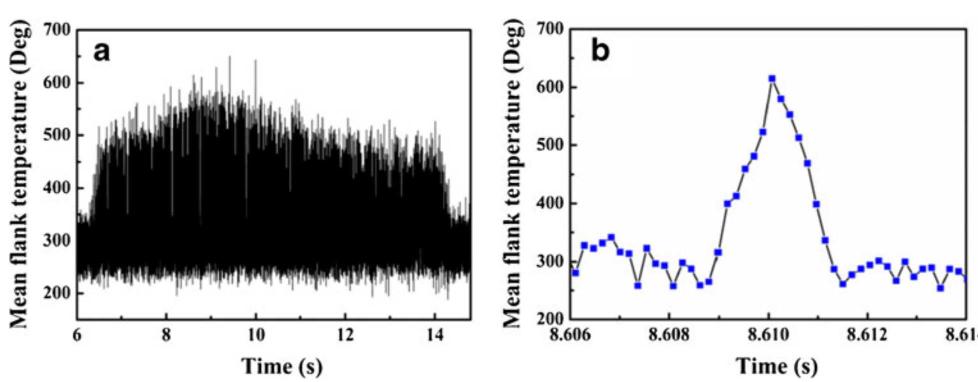

Fig. 5 Relationship between the mean flank temperature and the time of cutting, v_c=628 m/min. **a** The whole milling process. **b** A cutting period in **a**

Table 5 The setting of tool emissivity at different cutting speeds

Cutting speed (m/min)	Uncoated carbide tool	TiN/TiAlN PVD-coated carbide tool
62.8	0.73	0.75
125.6	0.73	0.85
251.2	0.85	0.85
376.8	0.875	0.92
502.4	0.875	
628	0.875	

600 °C) when the cutting speed is higher than 125.6 m/min. This may be because there is no contact between the flank face and chip or workpiece (no heat generating from friction and plastic deformation, only heat transferring). At present, most researchers have concluded that there is no reduction in temperature at high-cutting speed; contrarily, a much higher tool interface temperature is generated [37]. In this study, the temperature variation of tool flank face was investigated, which was different from the variation of tool–chip or tool–workpiece interface temperature. In the high-speed machining, the heat generated in tool rake face and plastic deformation zone does not have enough time to spread to the flank face with the increase of cutting speed. Therefore, it is possible that the mean flank temperature is almost kept constant when the cutting speed is higher than 125.6 m/min for uncoated inserts.

3.3 Tool wear

In the milling process of the titanium alloy, the tool wear progresses rapidly due to the high temperature and strong adhesion between the tool and workpiece materials. Figure 7 shows the SEM photographs of uncoated carbide tools at different cutting speeds. From Fig. 7a, c, the adhesion of chips onto the rake face of the uncoated carbide is observed when the cutting speed is changed from 62.8 to 628 m/min in end

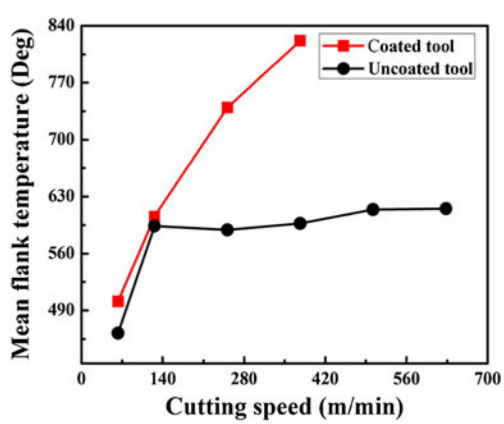

Fig. 6 Effect of cutting speed on the mean flank temperature

milling of Ti-6Al-4V alloy. Figure 7b, d show the adhesion of the workpiece materials on the cutter edge. Based on the results, the adhesion always appears in milling of Ti-6Al-4V alloy whether at higher or lower cutting speed.

In contrast, Fig. 8 shows SEM photographs of TiN/TiAlN PVD-coated carbide tools after cutting; from Fig. 8a–c, the adhesion of the micro-chips on the rake face is observed when the cutting speed is changed from 62.8 to 251.2 m/min; however, the adhesion of workpiece materials cannot be seen on the flank face. As the cutting speed increases, the serious adhesion of workpiece materials around the cutter edge can be observed clearly when the cutting speed is 376.8 m/min, as shown in Fig. 8d.

In order to assess tool wear, the tool surfaces were etched in solution with 2 % HNO_3+3 % HF+95 % H_2O until the titanium alloy adhered on the tools was removed absolutely. Figure 9 shows the SEM photographs of the etched carbide inserts. The abrasion cannot be seen as the increase of cutting speed, only a small notch wear occurs on the cutting edge when the cutting speed is 628 m/min (see Fig. 9d). However, the cutting time is only 7.962 s. If the cutting time is longer, the tool life at the cutting speed of 628 m/min might be short because of the high-cutting force (see Fig. 3).

Figure 10 shows the SEM images of the etched TiN/TiAlN PVD-coated carbide tools at different cutting speeds. When the cutting speed is 62.8 m/min, the phenomenon of coating delamination on main cutting edge is observed clearly (see Fig. 10b). When the cutting speed is 251.2 m/min, coating delamination not only appears on the main cutting edge, but also appears on the cutter tip, as shown in Fig. 10c, d. As the cutting speed is further increased, besides increasing coating delamination, the thermal crack (perpendicular to the rake face, see Fig. 10f) can also be found. And the flank wear VB is up to 0.4 mm at a speed of 376.8 m/min (see Fig. 10e). Based on the experiment results, an increase in cutting speed tends to accelerate coating delamination, which exposes tool substrate to the extremely high temperature environment. Hence, several obvious thermal cracks, thermal fatigue and chemical reaction at high temperature quickly bring the cutting tool edge catastrophic failure.

In addition, as presented in Fig. 10h, the chipping of the cutting edge can be observed at the cutting speed of 376.8 m/min, which is another important factor in tool failure except for the thermal crack. The excessive chipping of cutting edge tends to weaken the bond strength of tool substrate, consequently accelerates tool wear. In general, hardness and thermal conductivity are very important properties for a cutting tool since they are strongly related to the resistance of wearing and chipping of the cutting tool. The TiN/TiAlN PVD-coated inserts can extend tool life in the machining of difficult-to-cut material for its high hardness. According to the experiment results, the cutting force and cutting temperature of TiN/TiAlN PVD-coated inserts and uncoated inserts are

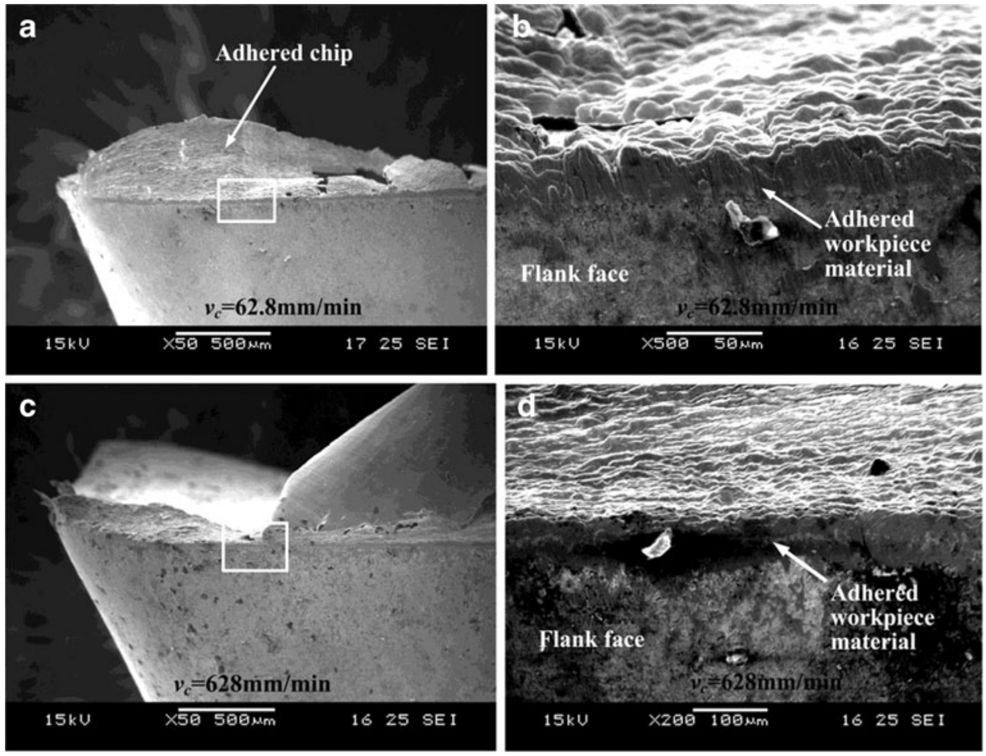

Fig. 7 SEM photographs of uncoated carbide tools at different cutting speeds. **a** Cutting speed v_c=62.8 m/min, cutting time t= 79.62 s. **b** Rectangular region of **a**. **c** Cutting speed v_c=628 m/min, cutting time t=7.962 s. **d** Rectangular region of **c**

low at a lower cutting speed (below 125.6 m/min). Under this condition, the coated inserts can extend tool life. However, at a high-cutting speed, its low-thermal conductivity (TiN: 19 W/(M·K), tungsten carbide: 100 W/(M·K)) will result in high temperature on the tool interface which can weaken the bond strength of tool substrate and then accelerate tool wear. Furthermore, there are some workpiece materials adhered to the unevenly worn surface of the tool flank, as shown in

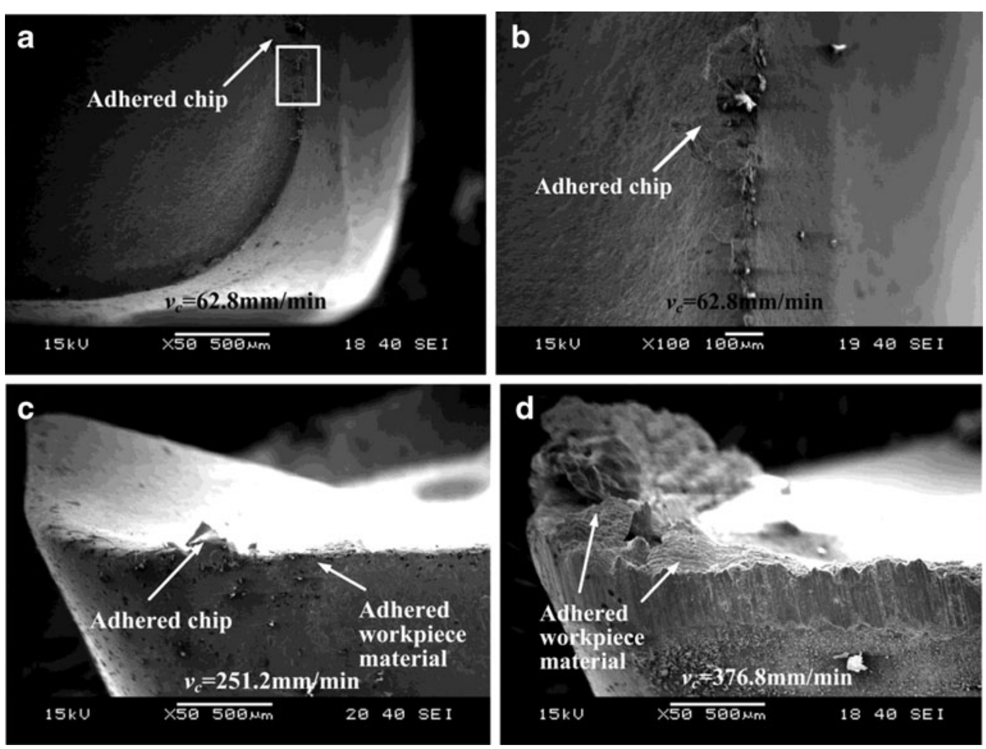

Fig. 8 SEM photographs of TiN/TiAlN PVD-coated carbide tools at different cutting speeds. **a** Cutting speed v_c=62.8 m/min, cutting time t=79.62 s. **b** Rectangular region of **a**. **c** Cutting speed v_c=251.2 m/min, cutting time t=19.905 s. **d** Cutting speed v_c=376.8 m/min, cutting time t=13.27 s

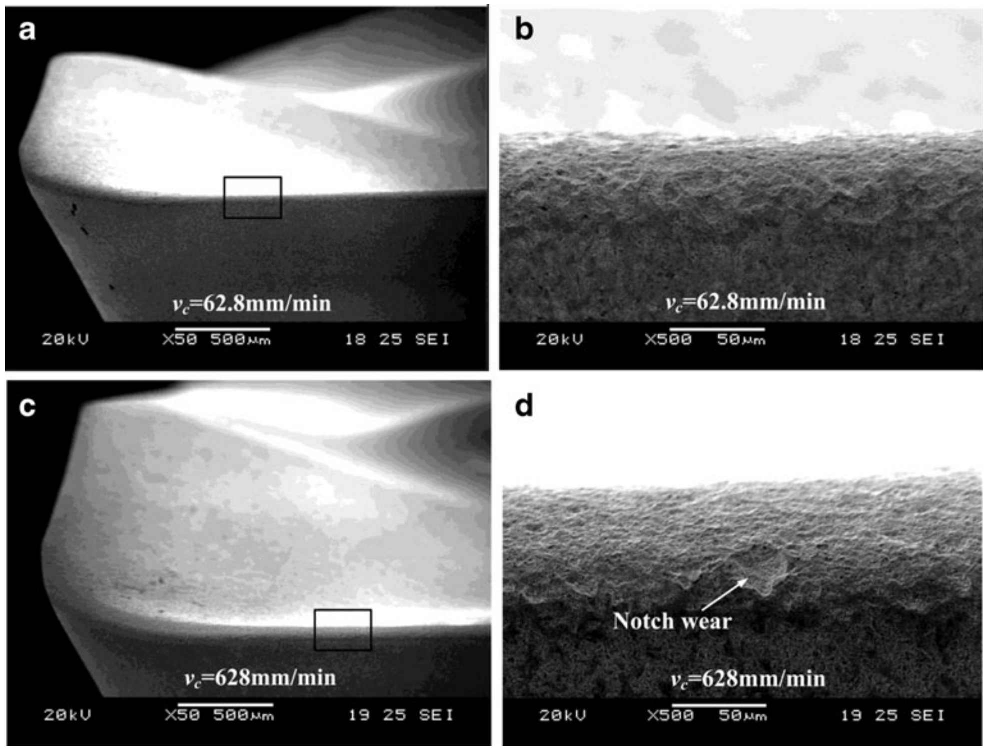

Fig. 9 SEM photographs of the etched uncoated carbide inserts at different cutting speeds. **a** Cutting speed v_c=62.8 m/min, cutting time t=79.62 s. **b** Rectangular region of **a**. **c** Cutting speed v_c= 628 m/min, cutting time t= 7.962 s. **d** Rectangular region of **c**

Fig. 10h. It is demonstrated that fragments of tool material have been taken away by the adhered workpiece materials. This accelerated attrition wear quickly. The obtained results show that TiN/TiAlN PVD-coated carbide tools are not suitable to machine Ti-6Al-4V titanium at higher cutting speed.

In summary, the machinability of Ti-6Al-4V alloy can be represented by cutting force, cutting temperature, and tool wear. The obvious decrease in cutting force cannot be observed as the increase of cutting speed, which is different from the light metals. However, it almost behaves to be constant whether the tool is uncoated carbide or TiN/TiAlN PVD-coated carbide when the cutting speed is changed from 62.8 to 125.6 m/min. The cutting force increases significantly when the cutting speed is higher than 125.6 m/min. The increase in cutting force is because the effect of strain hardening predominates over the effect of thermal softening at the elevated temperature. As for the cutting temperature, it is found that the mean flank temperature of uncoated carbide tools almost remains constant when the cutting speed exceeds 125.6 m/min. There is no obvious abrasion wear that could be observed on rake face and flank face for all cases except for a small notch wear on the main cutting edge. The mean flank temperature of TiN/TiAlN PVD-carbide tools always increases with increasing cutting speed on the same cutting condition. The reason for this is that TiN/TiAlN PVD-coated carbide tool has low-thermal conductivity and the heat on the tool face escapes slowly. Coating delamination, excessive chipping of the cutting edge, and thermal crack tend to weaken the bond strength of the tool substrate, which results in the failure of coated carbide tools. In conclusion, the coated carbide tools have poor performance at higher cutting speed.

4 Conclusions

In this study, a detailed analysis of cutting force, flank temperature, and tool wear at various cutting speeds has been carried on in end milling of titanium alloy Ti-6Al-4V using uncoated and TiN/TiAlN PVD-coated carbide tools. Based on the presented and discussed experimental results, the following conclusions can be drawn:

1. The cutting force almost behaves to be constant when the cutting speed is changed from 62.8 to 125.6 m/min whether the cutter is uncoated or coated carbide. However, the cutting force of both tools increases when the cutting speed is higher than 125.6 m/min.
2. As for the coated carbide tools, mean flank temperature increases as the increase of cutting speed. But for uncoated carbide tools, it is interesting that the mean flank temperature is almost constant (about 600 °C) when cutting speed is changed from 125.6 to 628 m/min.
3. The adhered chips or workpiece materials always appear on rake face and cutting edge for uncoated and coated tools at different cutting speeds. However, no obvious

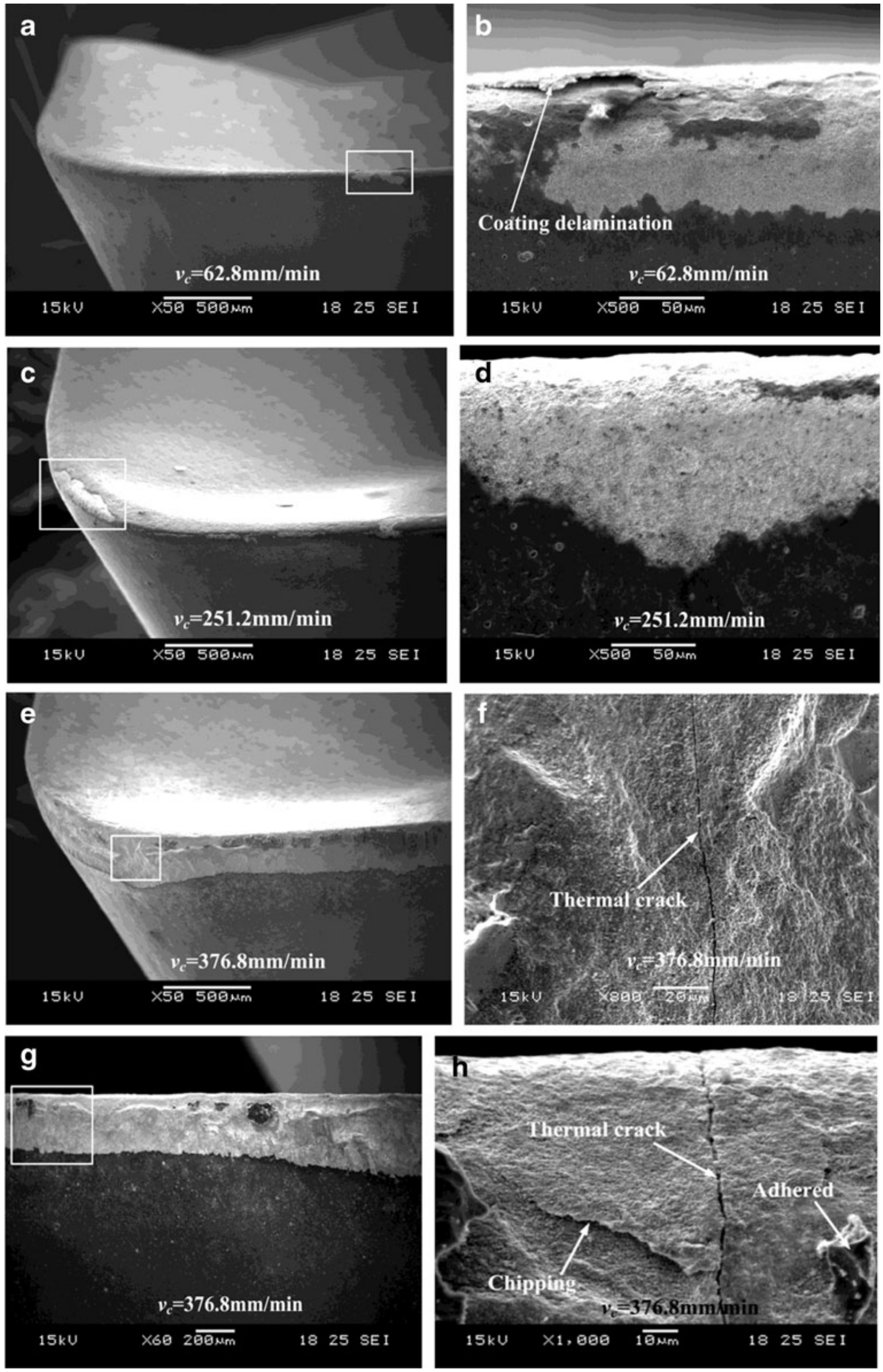

Fig. 10 SEM photographs of the etched TiN/TiAlN PVD-coated carbide inserts at different cutting speeds. **a** v_c=62.8 m/min, cutting time t=79.62 s. **b** Rectangular region of **a**. **c** v_c=251.2 m/min, cutting time t=19.905 s. **d** Rectangular region of **c**. **e** v_c=376.8 m/min, cutting time t=13.27 s. **f** Rectangular region of **e**. **g** v_c=376.8 m/min, cutting time t=13.27 s. **h** Rectangular region of **g**

abrasion wear or fatigue can be observed for uncoated carbide tools in the speed range of 125.6–628 m/min. In contrast, coating delamination, chipping of the cutting edge, and thermal crack can be found for the coated carbide tools in the high-speed milling.

4. The cutting performance of uncoated carbide tools is relatively better than TiN/TiAlN PVD-coated carbide tools in the high-speed milling of titanium alloy Ti-6Al-4V. However, the tool life of uncoated inserts at the higher cutting speed needs to be further researched. The tool life

of TiN/TiAlN PVD-coated inserts is short at higher cutting speed. So, it is not suitable to machine Ti-6Al-4V titanium alloy when the cutting speed is higher than 125.6 m/min.

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