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ORIGINAL ARTICLE

Investigation on diffusion wear during high-speed machining Ti-6Al-4V alloy with straight tungsten carbide tools

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Abstract During high-speed machining Ti-6Al-4V alloy, high-temperature at the tool–chip interface and the concentration gradient of chemical species between tool material and workpiece material support the activation of diffusion process, and therefore the crater wear forms on the rake surface of the cutting tool at a short distance from the cutting edge. In this paper, the diffusion analysis was theoretically proposed. The constituent diffusion at the contact interface between tool material and Ti-6Al-4V alloy at high-temperature environment, the crater wear on the rake surface of the tool, and the chips collected from high-speed milling Ti-6Al-4V alloy with straight tungsten carbide tools were analyzed by the scanning electron microscope with energy dispersive X-ray spectroscopy. The constituents inside the tool could diffuse into the workpiece and the diffusion layer was very thin and close to the interface. Compared with the diffusion of tungsten and carbon atoms, the pulling out and removing of the tungsten carbide (WC) particles due to cobalt diffusion dominated the crater wear mechanism on the rake surface of the cutting tool.

Keywords Diffusion wear · Straight tungsten carbide tool · High-speed machining · Ti-6Al-4V alloy

1 Introduction

Titanium and its alloys have been experiencing extensive development over the past few decades stimulated by a series of their unique properties, such as high strength-to-weight ratio maintained at elevated temperature, high fracture resistance, and exceptional resistance to corrosion at temperature below 500°C [1]. Therefore, titanium and its alloys are widely used in many industries [2]. Commercial titanium alloys are classified conveniently in three different categories as alpha, alpha-beta, beta alloys according to their equilibrium constitution, which varies with the types and concentrations of alloy elements [3]. One of the most commonly used titanium alloys in the world is Ti-6Al-4V. Ti-6Al-4V is typical alpha-beta titanium alloy, which is usually used in aerospace, biomedical, automotive, and petroleum industries [4]. However, it is important to note that its low thermal conductivity and high heat capacity may cause difficulties in heat dissipation during cutting process, which result in high cutting temperatures concentrated at a narrow region adjacent to the cutting edge [5], where the temperature can reach as high as 1,000°C [6]. Another significant characteristic of titanium alloys is a very high chemical reactivity [7]. As a result, tool wear progresses rapidly [8], and then reduces the tool life and machining quality.

The extreme conditions (high temperature and pressure, intense friction, significant sliding velocity, etc...) at the tool–chip interface and the concentration gradient of chemical species between tool material and workpiece material support the activation of diffusion process and particles move toward areas of low concentration. The atoms diffusing from the tool into the chip are finally carried away by the flow of the chip along the contact surface. Consequently, the crater forms on the tool rake surface, which reduces the tool mechanical resistance and its efficiency. Diffusion phenomena of the cutting tools were first reported by Loladze [9, 10], who showed that at conventional speed, tool wear was mainly caused by

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Table 1 Normal chemical composition of tungsten carbide (WC-Co) (wt. %)

W	C	Co
78.63	12.7	8.67

Table 3 Normal chemical composition of Ti-6Al-4V alloy (wt. %) [21]

	Al	V	Fe	Si	C	N	H	O	Titanium
Min.	5.5	3.5	–	–	–	–	–	–	Balance
Max.	6.8	4.5	0.3	0.15	0.1	0.05	0.015	0.15	

abrasion and adhesion, but was dominated by diffusion process at higher speed. Diffusion wear for cutting speed greater than 150 m/min was illustrated by experimental results of Naerheim and Trent [11], who showed the existence of concentration gradients of tungsten, carbon, and cobalt within the chip at the tool–chip interface. Photographic evidence provided by Trent [12] showed a smooth crater surface with no deformation of tungsten carbide particles in the tool near to the tool–chip interface. These observations support the fact that abrasion wear do not operate at higher cutting velocities, and diffusion should be responsible for the crater wear on the rake surface of the tool.

Recently, some researchers focus on establishing the predictive crater wear model based on the diffusion at the tool–chip interface, and then the cutting parameters can be optimized further. Molinary and Nouari [13, 14] presented two different models of tool wear by diffusion of cemented carbide tools respectively into chips of 1018 steel and 42CrMo4 steel and both models had good agreements with respect to measurements of crater wear made by other published literatures. Jiang and Shivpuri [15] established an analytical wear model that relates crater wear rate of WC/Co tool to thermally driven cobalt from cutting tool into titanium chip and it was pointed out that the diffusion of cobalt dominated the crater wear mechanism. The predictive model was verified by the experimental results from published literatures and from high-speed turning. Until now, due to complexity of this problem, there are few models which can quantitatively reveal the diffusion performances at the tool–chip interface during high-speed machining Ti-6Al-4V alloy and their effects on the tool wear mechanism.

High-speed end milling of aluminum alloys is a relatively routine operation in making aerospace products. However, the applications of high-speed machining (HSM) in milling operations of titanium and its alloys are still relatively limited. Though ultra hard tool materials like cubic boron nitride (CBN) and polycrystalline diamond (PCD) perform better than other tool materials, the high cost of such cutting tools compel the machining industries to look for other options [16, 17]. Previous studies [16, 18] have shown that straight tungsten carbide (uncoated WC/Co) tools still remain the recommended tool when machining titanium alloys.

As mentioned above, during high-speed machining Ti-6Al-4V alloy with straight tungsten carbide tools, the diffusion wear on the rake surface is the predominant model of the tool failure, which affects productivity and manufacturing efficiency. To optimize the material removal rate and obtain desired surface quality and dimensional accuracy in the high-speed machining titanium alloys with straight tungsten carbide tools, the diffusion wear mechanism is an important factor to take into consideration. The first purpose of the present paper is to conduct the diffusion analysis at the tool–chip interface, which can provide a theoretical basis for investigating the crater wear on the rake surface of the tools. Then, the diffusion analysis at the tool–chip interface was verified by the experimental results from the diffusing samples at high-temperature environment and the chips collected from high-speed milling test with straight tungsten carbide tools.

2 Diffusion analysis at the tool–chip interface

It is now commonly agreed that the life of carbide tool used to machine Ti-6Al-4V alloy is limited by the diffusion flow at the tool–chip interface. Therefore, it is necessary to present a theoretical analysis model to estimate the atom diffusion of the tool material towards the chips during high-speed milling Ti-6Al-4V alloy.

The tool material is usually an alloy and consists of a few elements; for example, a cemented tungsten carbide material consists of atoms of carbon, tungsten, and cobalt.

Table 2 Mechanical properties and thermo-physical data of tungsten carbide (WC-Co) [19, 20]

Density (kg/m^3)	Bending strength (GPa)	Fracture toughness (MPa·m$^{1/2}$)	Hardness (HRA)	Young's modulus (GPa)	Thermal conductivity (W/m·K)	Expansion coefficient (μm/m·°C)
1,477	2,563	15.48	90.1	550–650	75–120	4.5–6.0

Table 4 Mechanical properties and thermo-physical data of Ti-6Al-4V alloy [22, 23]

Density (kg/m^3)	Specific heat capacity (J/g·°C)	Thermal conductivity at 24° (W/m·K)	Expansion coefficient at 100° (μm/m·°C)	Young's modulus (GPa)	Hardness (HRc)
4,500	0.502	6.785	10.064	113.8	30–36

The tool material used in this research was micro-grain straight tungsten carbides, which approximately consisted of 91.33 wt. % tungsten carbide with 8.67 wt. % of cobalt as binder (equivalent to ISO grade K30). According to the energy dispersive X-ray spectroscopy (EDS) analysis, the chemical composition of tungsten carbide (WC/Co) is listed in Table 1. The mechanical and thermo-physical properties of the tool material are listed in Table 2 [19, 20]. The chemical composition, mechanical, and thermo-physical properties of Ti-6Al-4V alloy are listed in Tables 3 [21] and 4 [22, 23], respectively.

In general, the tool wear on the rake surface of the tool in high-speed milling Ti-6Al-4V occurs mainly due to diffusion, and most of the diffusion occurs in a thin layer (some 10 μm thickness) below the rake surface of the cutting tool where the highest temperature is observed. Thus, the boundary surface between the tool rake surface and the chip can be represented as a plane [15]. In metal cutting process, the flow of chemical elements has two major origins. The first one is diffusion between tool and chips and the second one is the convective transport of material that moves on the tool surface [14]. To simplify the diffusion analysis at the tool–chip interface, we assume that the concentration gradient in the y-direction is small with respect to the gradient in the x-direction (Fig. 1). Accordingly, the diffusion process in this thin layer is governed by the tool–chip temperature which depends on x. The bidirectional constituent diffusions take place at the tool–chip interface under the action of high-temperature and high significant gradients of chemical species. However, in view of crater wear on the rake surface of the tool, we will focus on discussing the constituent diffusion of the cutting tool, i.e., tungsten, carbon, and cobalt, towards the chips.

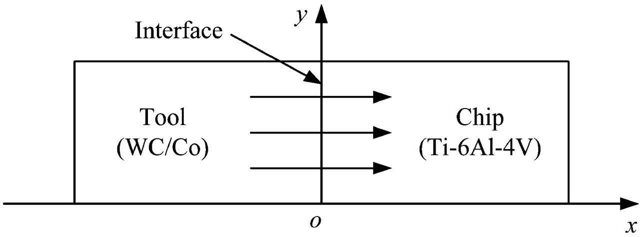


Fig. 1 Coordinates in the tool–chip diffusion interface

The diffusion between the cutting tool and the chips belongs to the non-steady state diffusion, i.e., the diffusion flux and the concentration gradient vary with depth below the rake surface of the tool and time. When the concentration varies along only one direction, say the x-axis, according to Fick's second law [15], the concentration profiles for non-steady state diffusion can be expressed as follows,

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) \tag{1}$$

where, C is concentration of material (kg/m^3), x is the depth below the rake surface of the cutting tool (m), and D is diffusion coefficient (m^2/s).

To simplify the theoretical analysis of the diffusion process at the interface, we assume that the diffusion coefficient is independent of chemical composition, Eq. 1 becomes

$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial x^2} \tag{2}$$

For the one-dimensional diffusion at the tool–chip interface, the concentrations of tungsten, carbon, and cobalt are held constant; therefore, the second-order partial differential diffusion equation requires two boundary or initial conditions to obtain a unique solution.

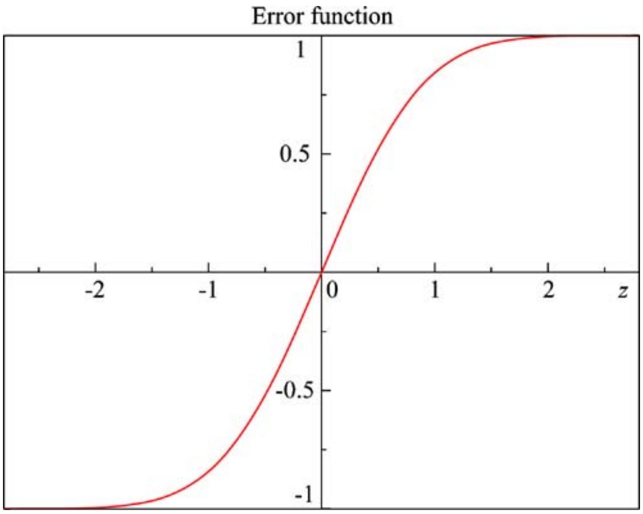


Fig. 2 Curve of error function

Table 5 Diffusion coefficient of the elements from cutting tool into chip [11, 12, 24] R=8.315/mol·K

Elements	Frequency factor D_0 (m^2/s)	Activation energy Q (J/mol)	Diffusion coefficient D (m^2/s)
W	2.475×10^{-1}	313,800	$D_w = 2.475 \times 10^{-1} \exp[-313,800/(RT)]$
Co	9.0×10^{-3}	334,720	$D_{Co} = 9.0 \times 10^{-3} \exp[-334,720/(RT)]$
C	1.5×10^{-5}	133,888	$D_C = 1.5 \times 10^{-5} \exp[-133,888/(RT)]$

1. Initial state: $C = 0$, for $x > 0$ and $t = 0$.
2. Left-hand boundary: At $x = 0$, C_0 is maintained for all $t > 0$.

Application of the above initial and boundary conditions to Eq. 2 yields the solution

$$C(x,t) = \frac{C_0}{2}\left[1 - \operatorname{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right] \tag{3}$$

where, $C(x, t)$ is the concentration at depth x after time t, C_0 is the initial concentration of tungsten, carbon and cobalt in tool material. The function “erf” in Eq. 3 is known as the Gauss error integral or Gauss error function. The error function, erf (z) is defined,

$$\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-\eta^2} d\eta \tag{4}$$

The error function is very important in analyzing the diffusion among different materials, whose value ranges from −1 to 1. The integral in Eq. 4 cannot be evaluated in closed form in terms of elementary functions; however, the relationship between the atom concentration and the error function can be qualitatively analyzed by the curve of error function in Fig. 2.

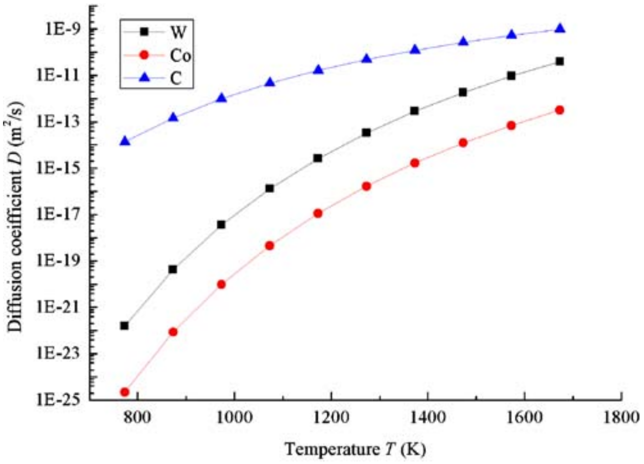


Fig. 3 Curves of diffusion coefficients at different temperatures

The diffusion coefficient D is assumed only a function of temperature but may change with time, as temperature gradually varies with time due to increasing wear. Furthermore, the diffusion rate of the constituents from the cutting tool into the chip is mainly determined by the concentration at the interface. From a thermodynamic and kinetic point of view, it is expected that the diffusion coefficient has a temperature-dependent Arrhenius expression [24]:

$$D = D_0 \exp\left(\frac{-Q}{RT}\right) \tag{5}$$

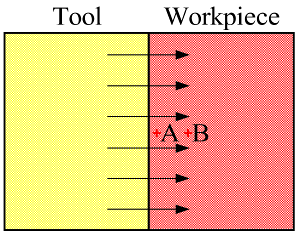
or

$$\ln D = \ln D_0 - \frac{Q}{R}\left(\frac{1}{T}\right) \tag{6}$$

where, D_0 is a temperature-independent frequency factor (m^2/s), Q is the activation energy for diffusion (J/mol), R is the gas constant (8.315/mol·K), T is the absolute temperature (K).

The activation energy is the energy required to produce the diffusive motion of one mole of the constituents. Large activation energy results in a relatively small diffusion coefficient (small diffusion flux). The corresponding data used in Eqs. 3 and 5 are listed in Table 5 [11, 12, 24], and the plots of the diffusion coefficients of various elements in tool material into the workpiece at different temperatures are illustrated in Fig. 3. From this figure, it can be seen that the diffusion coefficient of carbon is the largest one, followed by the diffusion coefficient of tungsten which is two orders of magnitude larger than that of cobalt at the same temperature. When time t, and depth x are fixed, the final concentration C (x, t) depends on the

Fig. 4 Schematic of diffusion experiment at high-temperature environment, **a** Bulk material of tool, **b** position A, **c** position B



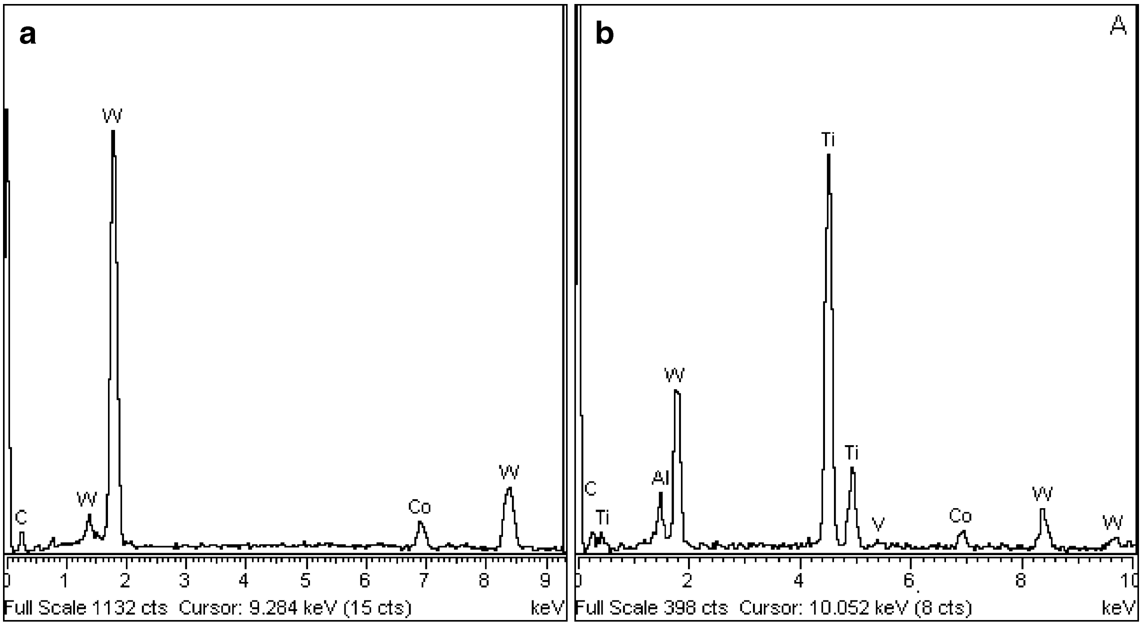
initial concentration C_0 and diffusion coefficient D. The workpiece is located in the positive direction of the x-axis (Fig. 1), the value of error function increases with the decrease of diffusion coefficient when the time and depth are fixed as shown in Fig. 2. Thus, combining Table 1, Eq. 3, and Fig. 2, it suggests that the final concentrations of tungsten and carbon are much higher than that of cobalt at the same cross-section of the workpiece after the same time.

3 Experimental verifications

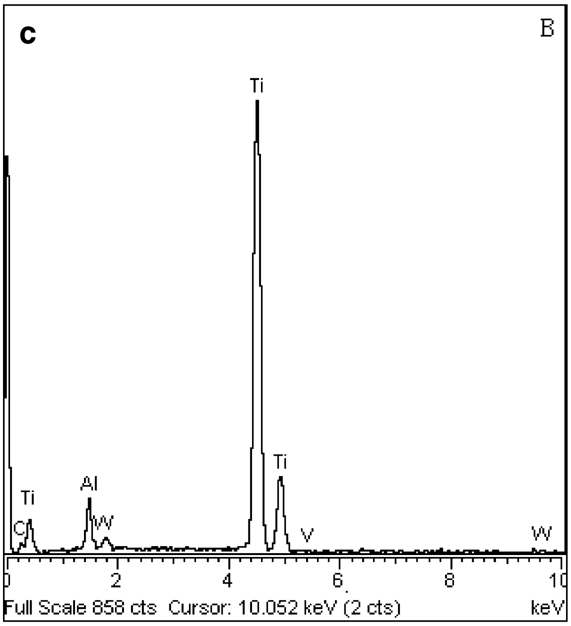
3.1 Experimental setup

3.1.1 High-temperature diffusion experiment

In order to mimic the diffusion process at the tool–chip interface, two polished specimens made of the carbide tool and the Ti-6Al-4V alloy respectively are fixed together as



a Bulk material of tool ***c Position B***



b Position A

Fig. 5 Chemical composition variation after high-temperature diffusion shown in Fig. 4. The arrows in Fig. 4 stand for the diffusion direction of the constituents inside the cutting tool material towards Ti-6Al-4V alloy. The diffusion experiment was performed at 773 K in a heating furnace for 1.5 h. Finally, the constituent diffusion at the contact interface was observed by using the scanning electron microscope (SEM) with energy dispersive x-ray spectroscopy. In order to investigate the diffusion concentration variation and the diffusion distance of various elements, two measurement locations were selected. Point A is very close to the contact interface, which is located 0.5 μm off the interface; while point B is a little far away from the contact interface, which is located 1.5 μm off the interface.

3.1.2 High-speed milling experiment

The Ti-6Al-4V block of size 120 × 100 × 20 mm was used in the high-speed milling tests. The cutting tool used in the machining tests was a 25 mm-diameter indexable milling cutter with single straight tungsten carbide insert. The tool geometry is as follows: the rake angle $\gamma_0 = +5°$, the axial rake angle $\gamma_p = +5°$, and the radial rake angle $\gamma_f = -2°$. The axial depth of cut a_p was 1.5 mm. The radial depth of cut a_e was 1 mm. The feed per tooth f_z was 0.1 mm. The cutting speed v_c was 150 m/min. All the machining tests were carried out on a CNC vertical machining center without any cutting fluids.

Milling tests were interrupted at regular intervals to measure and study the growth of crater wear with machining time. The crater profiles on the rake surface of the cutting tool were examined by using the SEM system. Meantime, to study the diffusion of various elements of tool material into the chip, some chips were collected from each cutting test and the chip micrographs and their chemical composition variation were obtained by using the same SEM/EDS system.

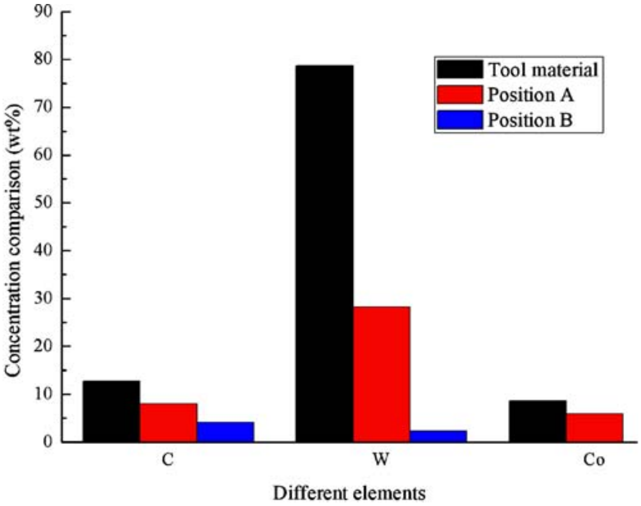
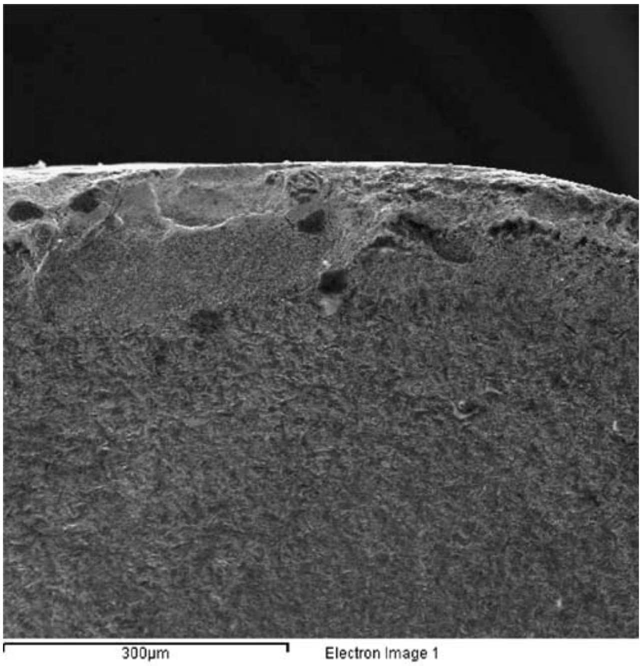


Fig. 6 Relationship between final diffusion concentration and distance, **a** after 6 min of milling, **b** after 18 min of milling

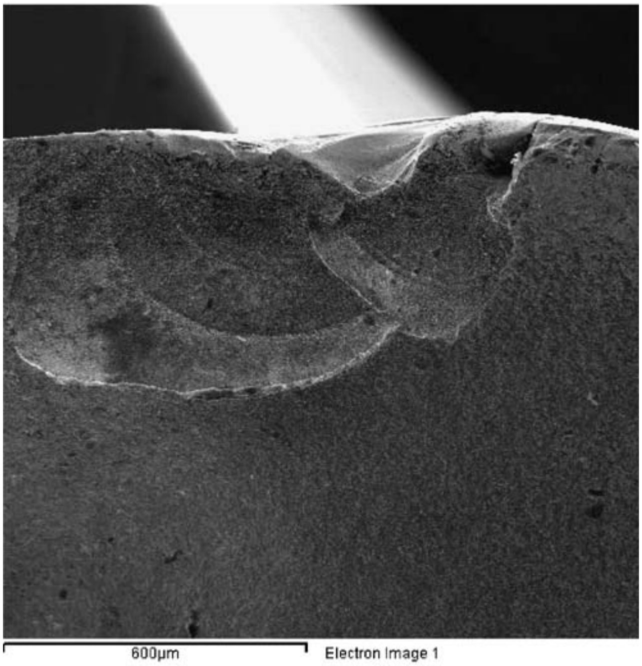
3.2 Results and discussion

3.2.1 High-temperature diffusion experiment

As shown in Fig. 5a, the normal chemical compositions of the cutting tool material were tungsten, cobalt, and carbon.



a after 6 minutes of milling



b after 18 minutes of milling

Fig. 7 SEM view of crater wear on tool rake surface

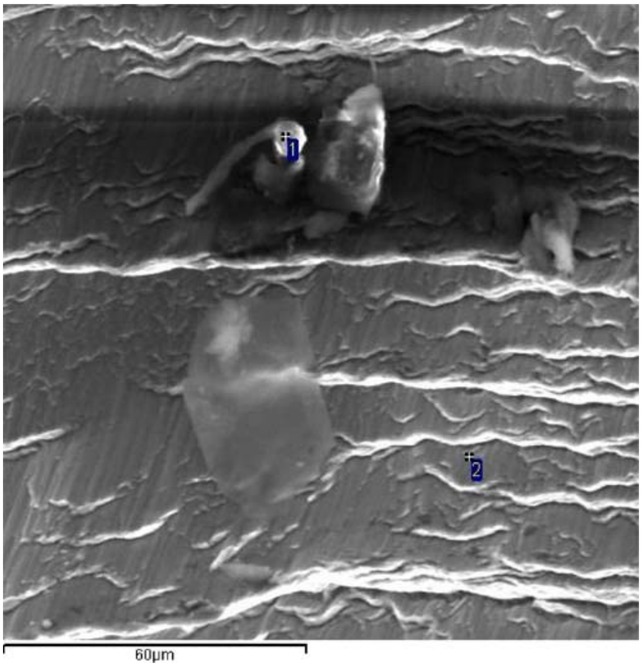


Fig. 8 Micrograph of chip back surface, **a** WC particles, **b** Bulk material of workpiece

During high-temperature diffusing process, the atoms inside the cutting tool, such as tungsten, cobalt, and carbon all diffused towards the workpiece under the action of thermal energy. The EDS analysis in Fig. 5b suggests that tungsten, cobalt, and carbon were all observed at the region very close to the interface. However, the finial diffusion concentrations of tungsten, cobalt, and carbon all decreased with the increase of depth below the tool–workpiece interface. As shown in Fig. 5c, the final diffusion concentration of tungsten and carbon became very low at the far region from the interface, and the cobalt atoms could not be observed once more. Thus, it's reasonable that the diffusion layer is very thin and very close to the interface.

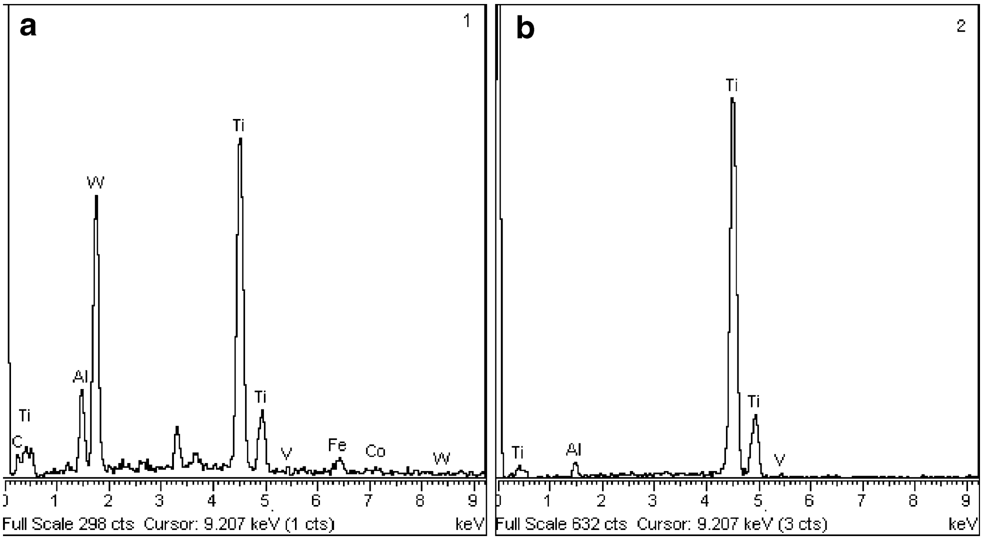
Due to the differences of the initial concentration and diffusion coefficient of various elements, the final concentration of different elements appeared significantly different even at the same depth as shown in Fig. 6. Obviously, the final diffusion concentrations of tungsten and carbon were much higher than that of cobalt, which coincide with the analysis results in Section 2, i.e., the number of tungsten and carbon atoms which could diffuse toward to Ti-6Al-4V alloy was much larger than that of cobalt atoms.

During high-temperature experiment, the tool and workpiece samples kept still, and there was no relative motion at the contact interface. However, high-speed milling process is much more complex, and there exist high temperature, high contact stress, and high relative motion between the tool and the chips. Though the diffusion experiments at the high-temperature environment can not entirely reflect the diffusion wear on the rake surface of the tool due to the complexity of the high-speed machining process, the EDS analysis can be a benefit and help us analyze the diffusion of cutting tool material towards the chips.

3.2.2 High-speed milling experiment

The properties of sintered WC/Co composites are critically dependent on their final composition and structure. Tungsten carbide (WC) is the main metallic hard material used. The role of cobalt in cemented carbides is to provide a ductile bonding matrix for tungsten carbide particles. Cobalt is used as a bonding matrix because its wetting or capillary action during liquid phase sintering allows the achievement of high densities.

Fig. 9 EDS analysis of chip



***a* WC particles** ***b* Bulk material of workpiece**

The relatively small contact length, the thin flow zone and the thin chip produced when machining titanium alloys are the main reasons for the high-temperature generated at the interface. It has been reported that the temperature at the tool–chip interface can reach up to 1,000°C [6]. The high-temperature and the intimate contact on the tool–chip interface provide an ideal environment for the diffusion of the constituents of tool material across the tool–chip interface.

In high-temperature diffusing process, the decrease of hardness and wear-resistance of tool material were mainly caused by the constituent diffusion, especially the tungsten and carbon diffusion towards the workpiece. However, during high-speed milling process, there is a large relative motion between the tool and the chips, and the chips usually rapidly flow on the tool rake surface. Even though the final diffusion concentration of cobalt was lower than that of tungsten, the diffusion of cobalt resulted in weakening the strength of WC, the friable and brittle WC crystals fractured away as soon as exposed, and then the WC particles could be pulled out and removed by the flowing chip over the rake surface of the tool. From the point of view of cutting performances, the removing of WC particles due to cobalt diffusion was much more deleterious to the hardness and wear-resistance, which resulted in the crater formation on the rake surface of the tool at a short distance from the cutting edge as shown in Fig. 7a after milling 6 min. It should be noted that the crater profile on the tool rake surface was not as regular as that occurs under turning conditions because the periodical entry and exit of tool teeth. With the increase of milling time, much more atoms inside the tool material diffused towards the chips, and much more WC particles were pulled out and taken away by the flowing chips. As shown in Fig. 7b, the crater wear gradually became deeper and deeper after milling 18 min, which resulted in a large positive rake angle and ultimately leading to catastrophic edge failure.

The cobalt diffusion can result in the WC particles are pulled out and taken away by the flowing chips. Thus, it's possible to find WC particles and cobalt atoms on the chips. Figure 8 is the micrograph of the back surface of the chip, and the white spot indicated the existence of WC particle. In addition, cobalt atoms were found around the WC particles as shown in Fig. 9a, while Fig. 9b is the EDS analysis of bulk material of the workpiece. The existences of WC particles and cobalt atoms on the back surface of the chip indicated that WC particles could be pulled out and taken away by the flowing chips.

Under the action of thermal energy, if there was no relation motion at the tool/workpiece interface, the final diffusion concentrations of tungsten and carbon were much higher than that of cobalt and the diffusion of tungsten and carbon was the dominant factor influencing the hardness and wear-resistance of cutting tool material. However, during high-speed milling process, the rapid flowing chips could pull out and take away WC particles once the cobalt binder surrounding the WC particles diffused outside and arrived at the tool–chip interface. Compared with the diffusion of tungsten and carbon atoms, the pulling out and removing of WC particles due to cobalt diffusion was the dominant factor which could decrease hardness and wear-resistance and result in the crater formation on the tool rake surface.

4 Conclusions

The diffusion analysis of the constituents inside the straight tungsten carbide tool towards the workpiece was conducted, and the theoretical analysis was verified by the diffusion experiments at high-temperature environment and high-speed machining tests. The key findings are summarized as follows

1. The diffusion analysis was theoretically proposed, which was verified by the following experimental results.
2. Under the action of thermal energy, the constituents inside the tool could diffuse into the chips (Ti-6Al-4V alloy), and the diffusion layer was very thin and very close to the tool–chip interface.
3. Cobalt diffusion led to the dislodging and breakaway of the WC particles, and the pulling out and removing of WC particles was much more deleterious to the hardness and wear-resistance than the diffusion of tungsten and carbon. It's reasonable that the pulling out and removing of the WC particles due to cobalt diffusion dominated the crater wear mechanism.

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