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ORIGINAL ARTICLE

Tool wear mechanisms involved in crater formation on uncoated carbide tool when machining Ti6Al4V alloy

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Abstract When machining titanium alloys at cutting speeds higher than 60 m/min using cemented carbide cutting tools, the tool wears out rapidly. With the ever-increasing use of titanium alloys, it is essential to address this issue of rapid tool wear in order to reduce manufacturing costs. Therefore, the intention of this study was to investigate all possible tool wear mechanisms involved when using uncoated carbide cutting tools to machine Ti6Al4V titanium alloy at a cutting speed of 150 m/min under dry cutting conditions. Adhesion, diffusion, attrition, and abrasion were found to be the mechanisms associated with the cratering of the rake surface of the cutting tool. The plastic deformation of the cutting edge was also noticed which resulted in weakening of the rake surface and clear evidence has been presented. Based on this evidence, the process of the formation of the crater wear has been described in detail.

Keywords Tool wear · Ti6Al4V · Crater wear · Adhesion · Attrition · Diffusion · Abrasion

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1 Introduction

Several hundred research articles have been out on the titanium machining over the past few decades [1–4]. All the initial research work has been focused on understanding the titanium material and its behaviour during machining and later focus on the machinability of the titanium and finally improving it [3]. To increase the productivity on the titanium machining shop floor, it is essential to either improve the material removal rate and/or the cutting tool life. In order to achieve the improved machinability of titanium, there are few critical factors to consider such as machining parameters, vibration, type of cutting tools/inserts used and also coolant delivery mechanisms [5–10]. Tool wear is considered as one of the major problems when machining titanium alloys. Worn tools can have deleterious impact on the surface quality and the dimensional accuracy of the machined component. Therefore, they need to be rigorously assessed for critical wear and replaced, leading to reduced machining cycle time.

In turning, there are quite a number of tool wear mechanisms. It is always quite difficult to identify a dominant tool wear mechanism for a specific machining condition. Trent and Wright [11] have reported that in the case of tungsten carbide tools, carbide grains were observed at the tool/work interface. The small tool-chip contact length in association with high thermo-mechanical stresses presented in the cutting region results in rapid thermo-mechanical wear of the cutting tools when machining titanium alloys [12]. In addition, the high chemical reactivity of titanium with most cutting tool materials further limits the life of the cutting tool which leads to excessive chipping, premature tool failure, and poor surface finish [13].

A number of studies have been focused on investigating the dominant tool wear mechanism when machining Ti6Al4V alloys using tungsten carbide inserts while turning [12, 14, 15]. Adhesion, abrasion and diffusion are considered to be the major tool wear mechanisms involved when machining titanium alloys using cemented tungsten carbide cutting tools. The wear of the cutting tool is not only dependent on the mechanical and physicochemical properties of the workpiece and the cutting conditions but also on the interaction of the workpiece material with the surface of the tool. Moving forward from experimental optimisation to simulation-based optimisation, it is critical to simulate the combined effects of thermo-mechanical wear process in dynamic conditions. For this reason, it is essential to critically understand the process of evolution of wear on the cutting tool surface.

It is well known that high temperatures generated when machining titanium alloys trigger the diffusion process between the chemical constituents of the workpiece and the cutting tool present in the cutting region. The temperatures generated in the vicinity of the cutting zone can reach as high as 800 °C depending upon the cutting conditions and the workpiece-tool interaction [9, 16]. Jianxin et al. [17] reported that the elements of the cemented carbide tool, viz. tungsten (W), cobalt (C) and carbon (Co), can penetrate up to a depth of 20 μm into the titanium workpiece at 800 °C under stationary conditions. Zhang et al. [18] represented this stationary interface between the tool and chip using the model shown in Fig. 1. However, turning is a contact-based dynamic process. This mode of dynamic wear mechanism has been studied in this current work.

Moreover, most of the researches published have identified the dominant tool wear mechanism at industrial cutting speeds of 60–75 m/min. Therefore, in this study, the process of evolution of tool wear in relation to the crater wear formation at a high cutting speed of 150 m/min is put forth, wherein the key mechanism is not just diffusion-based or attrition-based wear, but a combination of adhesion-diffusion-attrition as well as plastic deformation of the cutting edge. There is a significant demand in the industry to achieve high productivity with the application of higher cutting speed (such as 150 m/min) and reduce cost while machining titanium components. Hence, this information is of utmost importance to critically understand the tool performance under such thermo-mechano-dynamic conditions to assess options to improve titanium machining productivity.

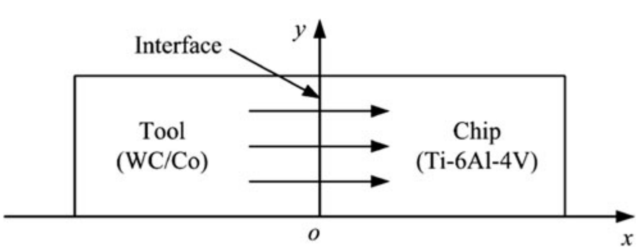

Fig. 1 Coordinates in the tool-chip diffusion interface [18]

The primary objective of the present work is to study the formation of crater wear on the rake surface of the uncoated WC-Co cutting inserts during turning of a Ti6Al4V workpiece. An investigation of wear of cemented carbide tools which is related to attrition and diffusion wear mechanism has been presented. An understanding of the crater wear at such high cutting speed will provide an insight assisting with the development of new cutting tools including different coatings on the WC tool substrate to improve machining of titanium alloys.

2 Experimental details

A solid bar of alloy Ti6Al4V 60 mm in diameter and about 150 mm in length were used for the machining trials. The hardness of this workpiece was 323±10 $HV_{0.5}$, and its microstructure is shown in Fig. 2. The average elemental composition (mass percentage) of the workpiece is given in Table 1.

A 3.5 hp Hafco MetalMaster Lathe AL540 was used for machining. Although better performing cutting tool materials have been developed for machining titanium alloys such as PCD [19], their relatively high cost compels the titanium machining industry to look for cheaper alternatives. Therefore, uncoated cemented carbide cutting tools still remain the recommended cutting tool material when machining titanium alloys. Hence, uncoated tungsten carbide tools CNMX1204A2-SM H13A manufactured by Sandvik Coromat along with the Sandvik tool holder were used. The insert had a rake angle of +15°, inclination angle of –6° and the entry angle of 45°.

Machining was performed under dry cutting conditions, i.e. neither any lubrication nor flood cooling was applied. The trial was conducted at a cutting speed of 150 m/min, feed rate of 0.214 mm/rev, and a depth-of-cut of 1 mm. The length of cut was kept between 95 and 110 mm.

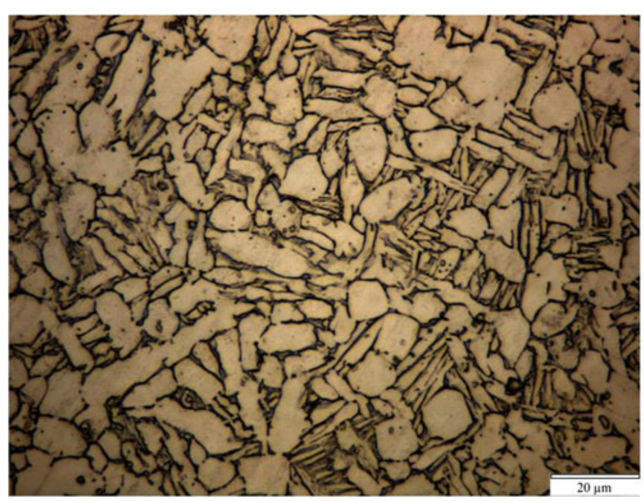

Fig. 2 Microstructure of the titanium workpiece used in this study

Table 1 Elemental composition of the titanium workpiece

Element	Al	V	Fe	C	N	H	O	Ti
Percentage	6.40	4.22	0.078	0.012	0.013	0.003	<0.2	Balance

A field emission scanning electron microscope, model Carl Ziess Supra 40 VP, was used to study the wear regions of the cutting tool inserts.

3 Results

Dry machining of the Ti6Al4V workpiece was carried out at a cutting speed of 150 m/min to study the tool wear process. The tool failure criterion was set as per the ISO 3685 standard, wherein the cutting tool was considered to have worn out when either the average flank wear was measured to be 300 μm or the maximum flank wear was measured as 600 μm. After a cutting time of 180 s, the tool wore out with the maximum flank wear reaching the failure criterion. The rake surface of the cutting tool was then studied under a secondary electron microscope (SEM).

The crater observed on the cutting tool was about 1.5 mm wide and 500 μm broad (as observed in Fig. 3). Throughout this crater, several regions were noticed where titanium adhered to the cutting tool, and at a few sites the underlying carbide tool was visible. Beyond the chip contact zone, regions of deposited titanium particles were noticeable. Furthermore, the back surface of the flowing chips smeared across the chip breaker, leaving regions of titanium residue. The elements were confirmed using energy-dispersive x-ray spectroscopy (EDS) spectral analysis and the results are presented in Fig. 3c.

It was noticed that towards the bottom of the crater region, thick layers of titanium adhered to the cutting edge forming titanium built-up edges. This observation was more predominant near the nose of the cutting tool and the edge closer to the end of the tool-chip contact area, as shown in Fig. 4. Moreover, the titanium accumulated on these built-up edges, forming vine-like features.

Within the crater region, the adhered titanium layer showed marks caused due to attrition as shown in Fig. 5. A number of dislodged particles from the titanium layer were noticed alongside the regions where the underlying tool surface was visible. Furthermore, at several locations, the adhered titanium layer was about to be peeled off the crater surface.

Further investigation was carried out to check whether the chemical constituents of the cutting tool, viz. tungsten (W), cobalt (Co), and carbon (C), diffused into the adhered titanium layer. The presence of carbon and tungsten on the adhered titanium was observed in the backscattered electron image from several regions in the crater. One of these regions showing the presence of these elements can be seen in Fig. 6. It was interesting to observe that the cobalt was not present on the adhered titanium layer. Apart from the crater, the carbon was also present in the deposited and smeared titanium regions as shown in Fig. 7. It was in the deposited titanium region where traces of cobalt were found.

4 Mechanisms of tool crater wear

When machining titanium, the high mechanical stresses present in the cutting region leads to abrasion of the cutting tool surface whereas the high temperatures generated within the cutting region facilitates the diffusion of the chemical constituents in the workpiece and the cutting tool [15]. Therefore, it is apparent that there can be accelerated tool wear due to the thermo-kinetic energies involved during machining. The following sections present the mechanisms involved in the formation of a crater on the rake face of the uncoated carbide cutting tool when machining titanium.

4.1 Formation of tool-chip interface

Prior to the commencement of diffusion upon the start of the cutting process, a tool-chip interface is formed due to the adhesion of titanium onto the surface of the cutting tool. Once this layer is thick enough,[1] it forms a stable diffusing interface, i.e. it acts as a steady platform for the transfer of elements from the cutting tool into the titanium chip and vice versa via diffusion, due to the high concentration gradient across the tool and the chips. Moreover, this interface is constantly replenished with the diffusing elements (Ti, Al, V, W, C and Co) from both the titanium chips and the carbide tool, as has been observed in Figs. 3, 4, 5 and 6.

Zhang et al. [18] reported that this diffusion interface can be up to 10 μm thick. The tool-chip interface is formed across the rake surface of the tool as long as the chip is in contact. For the cutting speed of 150 m/min used in this study, the tool-chip contact length was found to be about 1.5 mm wide and 500 μm broad. This is the initial contact zone wherein the tool-chip interface is formed. This region later forms the crater of the worn tool as can be seen in Fig. 3.

It is believed that the thickness of the tool-chip interface varies from the cutting edge until the end of the tool-chip interaction region, being thicker near the cutting edge than on the rake surface of the tool. This is due to the observation that the crater starts to form a short distance from the cutting

[1] It is extremely difficult to find the exact thickness of this interface on the tool rake face under an SEM, as the regions of the interface across the crater are at different stages of the wear process.

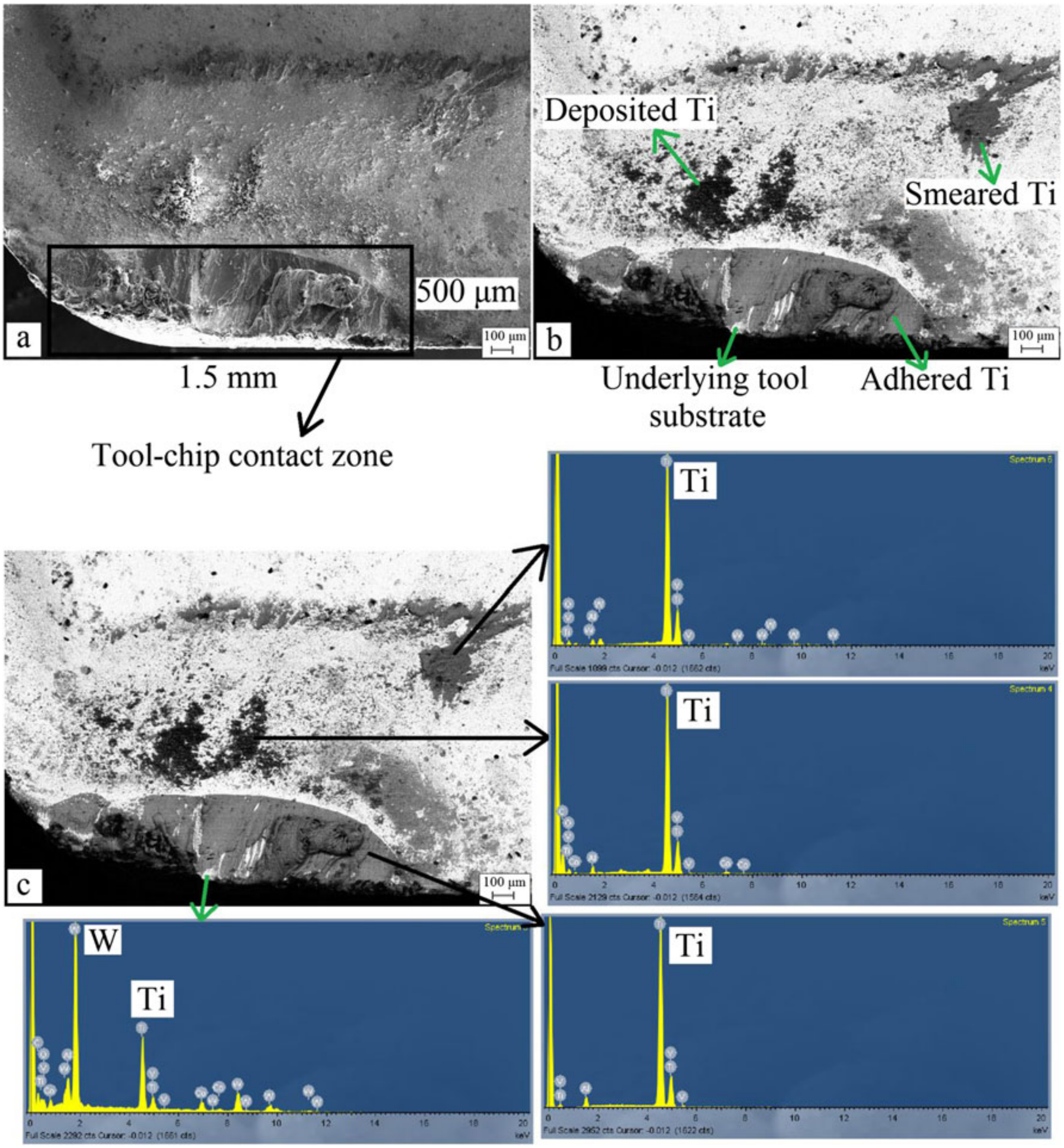

Fig. 3 Rake surface of the worn tool after dry machining of Ti6Al4V at 150 m/min, **a** secondary electron image, **b** backscatter electron image and **c** EDS spectrums showing the morphological and elemental variation across the worn tool rake surface

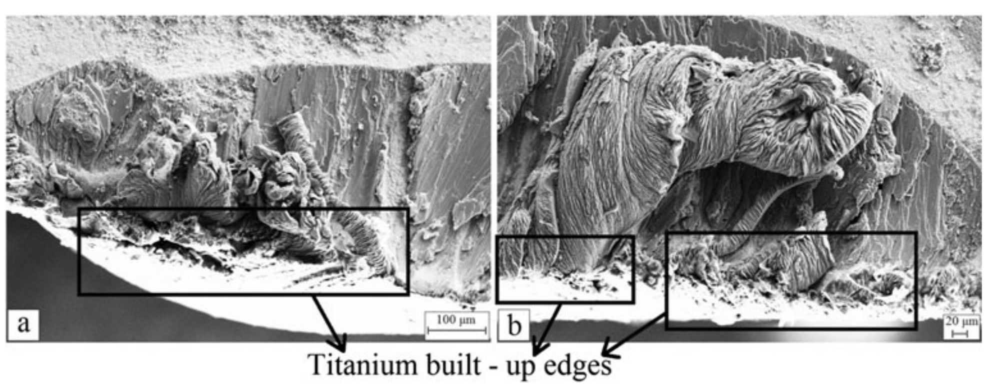

Fig. 4 Thick layers of titanium built-up edges adhered to the surface of the cutting tool near the **a** nose of the cutting edge, and **b** edge close to depth-of-cut

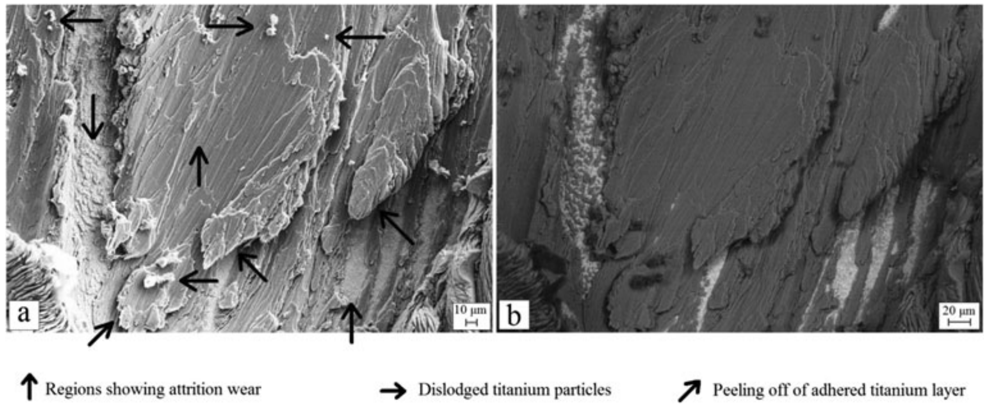

Fig. 5 Regions showing evidence of attrition wear due to the removal of the adhered titanium layer exposing the underlying tool layers to further wear

edge on the rake surface of the cutting tool [18]. A possible explanation for this observable fact is that the adhered titanium layer is thicker near the cutting edge than on the rake surface of the cutting tool, as shown in Fig. 4. This thick adhered layer, or sometimes referred to as built-up edge, hinders the formation of crater near the cutting edge.

Another explanation for the occurrence of crater wear away from the cutting edge is that the temperature generated in the vicinity of the cutting edge is lower than that produced at a short distance from the cutting edge. Both the analytical model developed by Komanduri and Hou and the experimental results reported in the literature that are used in their studies [20, 21] have clearly shown that the temperature is several hundreds of degrees higher at a certain distance from the cutting edge. This observation was attributed to the frictional heat added to the tool-chip interface during the cutting process along with the heat generated due to shear deformation of the flowing chips.

4.2 Diffusion of chemical constituents

Beyond the thick adhered titanium layer, a thin tool-chip interface is formed due to the subsequent flowing of titanium chips over the rake surface of the cutting tool over the tool-chip contact length. Once the tool-chip interface is established over the surface of the tool, the diffusion of the chemical constituents from both the flowing titanium chips over the interface and the cutting tool underneath the interface begins. From close examination of the rake surface of the worn tool under an SEM, it was found that there is predominant diffusion of carbon from the cutting tool towards the tool-chip interface, as compared with the other elements (W and Co) of the cutting tool, as observed in Fig. 6. In fact, only slight traces of tungsten on the tool-chip interface with no evidence of the diffusion of cobalt on this layer was noticed.

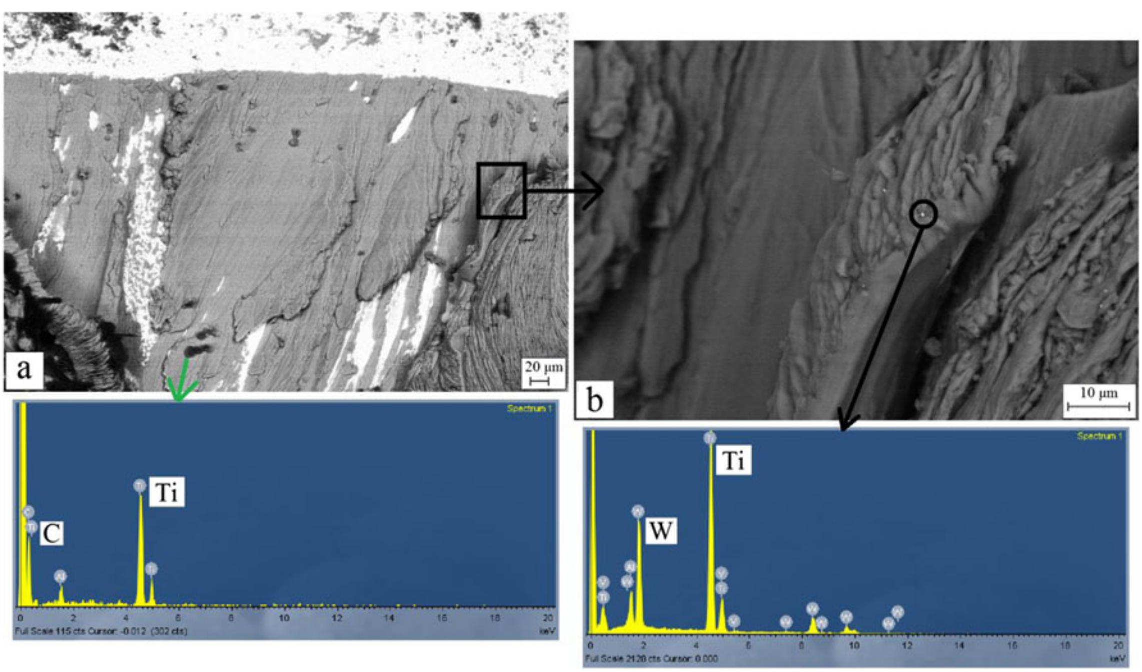

Fig. 6 Presence of **a** carbon and **b** tungsten on the tool-chip interface

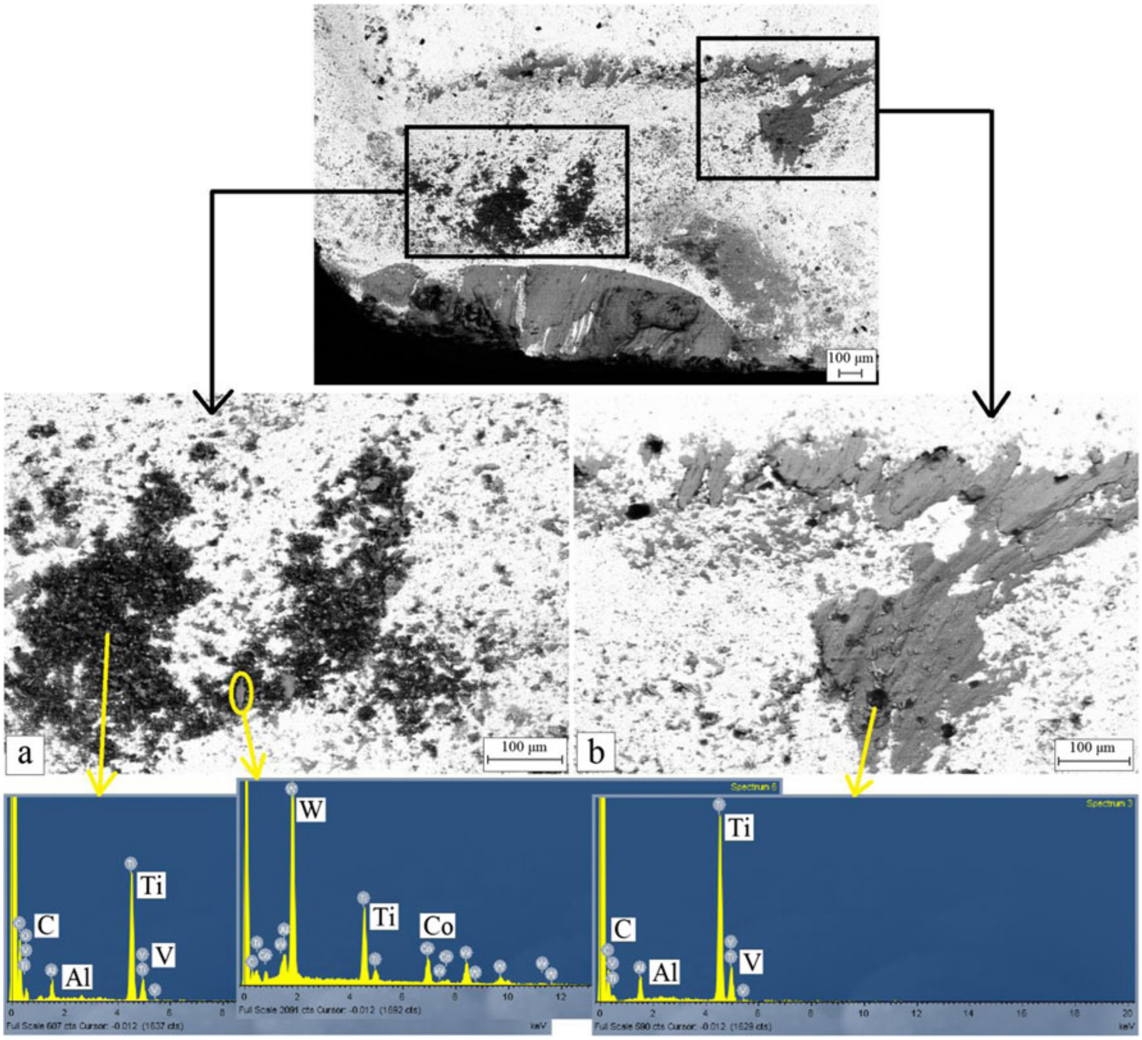

Fig. 7 Regions on the tool rake face where the tool-chip interface particles attached/deposited to the back surface of the chip

Zhang et al. [18] reported that the pulling out of tungsten carbide (WC) particles from the rake surface of the cutting tool due to the diffusion of cobalt was the dominant crater wear mechanism. Furthermore, Hua and Shivpuri [22] proposed an analytical wear model to calculate the crater wear rate of uncoated cemented carbide tools based on the diffusion of cobalt at conventional machining temperatures from the rake surface of the cutting tool into the titanium chips. Although the author's believe that the diffusion of cobalt is possible, however, this may not be the dominant diffusion mechanism of crater wear on cemented carbide tools, for the reason that the diffusion coefficient[2] of cobalt in titanium is almost twice the order of magnitude smaller than tungsten and far less than that of carbon, as presented in Fig. 8. Furthermore, Wang and Zhang [23] reported that the depth of diffusion of carbon in the tool-chip interface is more pronounced than that of cobalt.

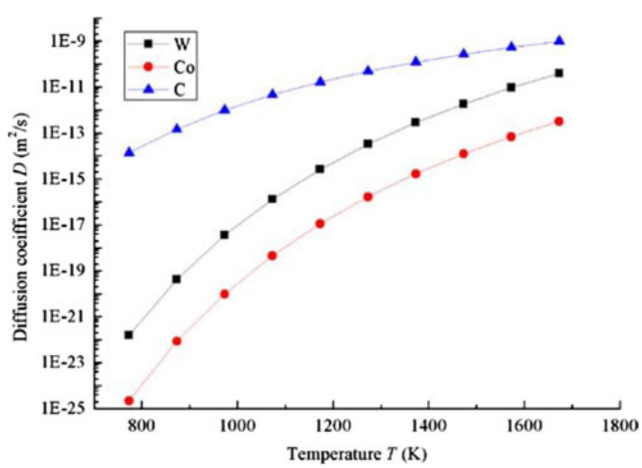

Fig. 8 Diffusion coefficients of the chemical constituents of an uncoated carbide cutting tool as a function of temperature [18]

[2] Diffusion coefficient is the diffusion mobility of one of the chemical elements among a pair of chemical species. The higher the diffusion coefficient of one substance with respect to the other, the faster the pair diffuses into each other.

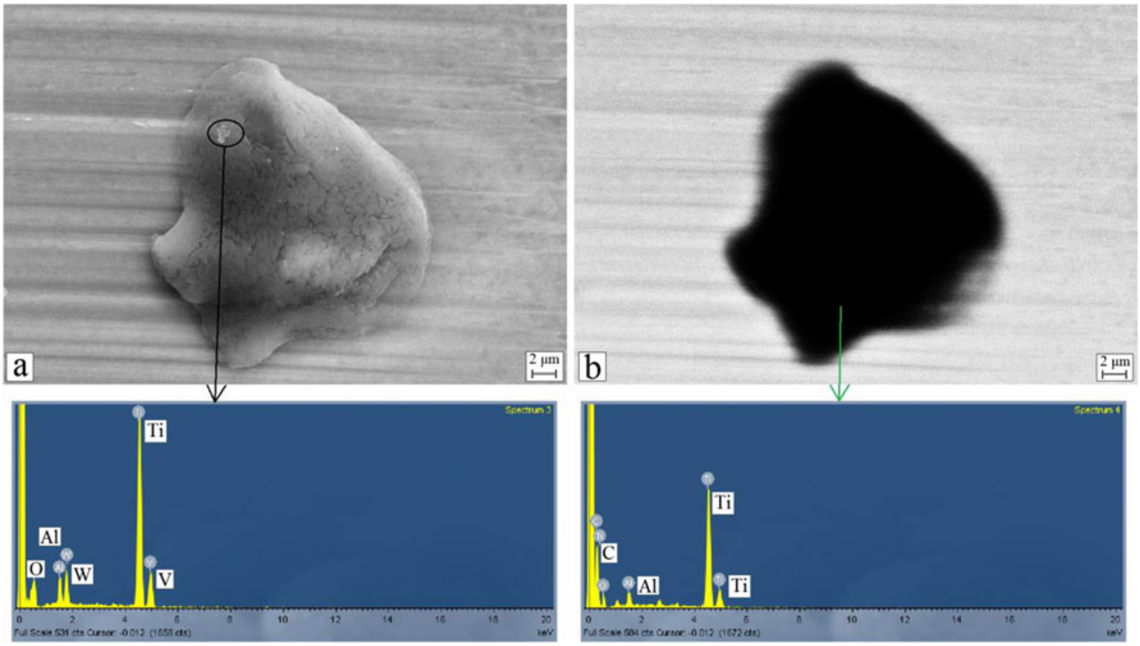

Fig. 9 A particle from the broken tool-chip interface clinging to the back surface of the titanium chip, **a** secondary electron image showing the presence of W, and **b** backscattered electron image confirming the presence of TiC from the tool-chip interface

On the other hand, titanium, being highly reactive with most tool materials, chemically combines with the diffused carbon present at the tool-chip interface to form titanium carbide (TiC), thereby maintaining the chemical gradient of carbon in the tool-chip interface. It is conceivable that at high cutting temperatures generated in the cutting region, tungsten carbide dissociates into individual elements, tungsten and carbon as reported by Nerz et al. [24]. This might promote the formation of titanium carbide. This newly formed compound diffuses towards the upper boundary of the tool-chip interface. EDS analysis shows the carbon that has diffused along the tool-chip interface as shown in Fig. 6a. This confirms that the carbon is either in the form of TiC or is present as a complex compound of Ti and C [25, 15].

4.3 Cratering of the rake surface of the cutting tool

Once the subsurface of the tool-chip interface loses a significant proportion of its strength, there is a tendency for this interface to become unstable in certain regions and rupture/fracture under the influence of high mechanical stresses. Small bits of the broken tool-chip interface dislodge and cling to the back surface of the flowing titanium chips. Figure 9 shows a particle clinging to the back surface of the titanium chip, which is a chemical compound of titanium and carbon as confirmed using EDS analysis. These displaced pieces might then further abrade the interface ahead of it, thereby tearing/breaking and dislodging more material from both the thin tool-chip interface and the underlying rake surface of the cutting tool, as shown in Fig. 5. This uncovers a new surface on the

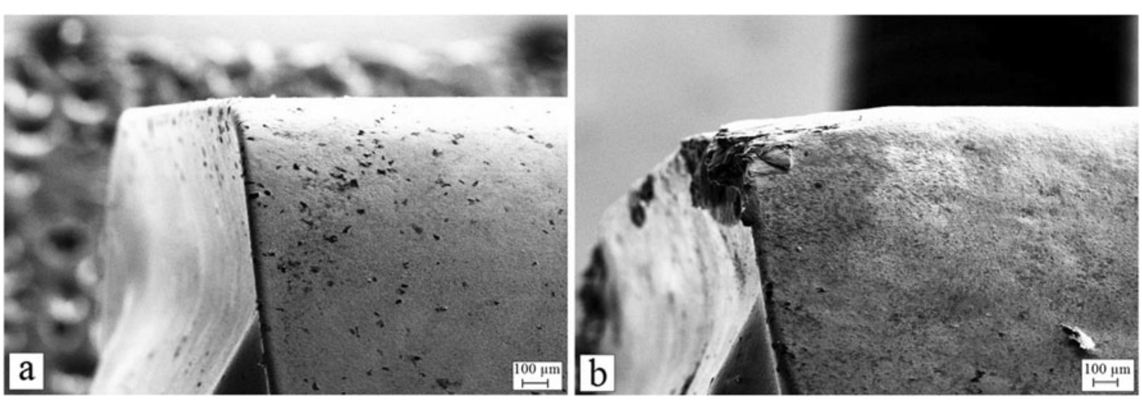

Fig. 10 Cutting edge of the **a** new tool in comparison with the plastically deformed edge of the **b** worn tool. Both **a** and **b** are secondary electron images

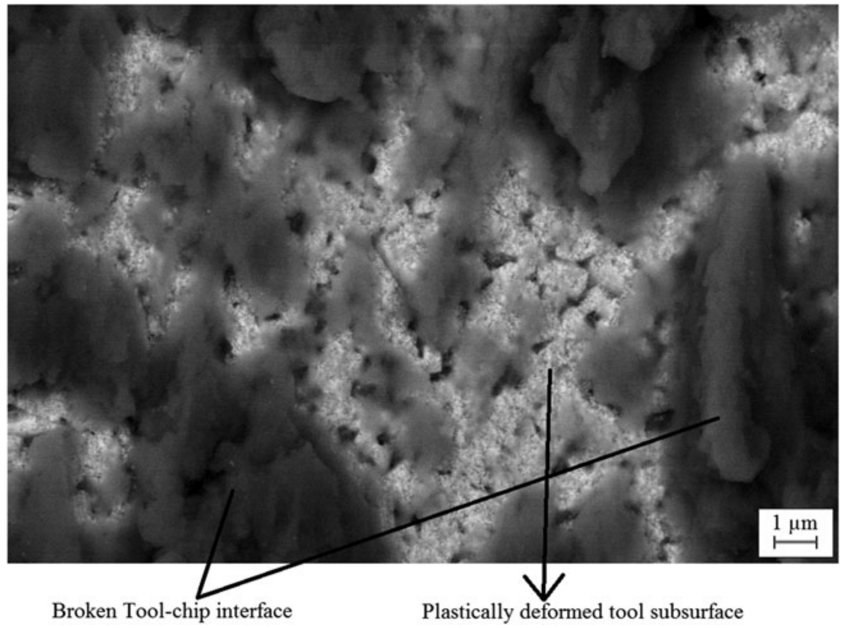

Fig. 11 High magnification backscattered electron image showing the plastic deformation of the tool subsurface due to excessive thermo-mechanical stresses generated during the cutting process

rake face of the cutting tool, exposing the tool to further wearing processes. Sequentially, a new titanium layer adheres to this freshly exposed region of the tool supplied by the unceasing flow of the titanium chips, forming another unstable tool-chip diffusion interface. This interface is then subjected to adhesion and abrasion phenomena, resulting in fracture and peeling off of this interface (Fig. 5). This process of reformation and breaking of tool-chip interfaces creates a crater of varying depths across the tool rake face.

4.4 Plastic deformation of the cutting edge

As the depth of crater increases, the cutting tool edge tends to weaken further due to the heavy loss of chemical constituents of the cutting tool. This creates sufficient mechanical stresses to plastically deform the cutting edge. Figure 10 shows the plastic deformation of the cutting edge after it has worn out during machining of the titanium alloy in comparison with the cutting edge of a new carbide tool. Moreover, the thermo-mechanical stresses generated in the cutting region can also plastically deform the tool subsurface beneath the tool-chip interface, as shown in Fig. 11. Therefore, the deformed edge increases the rake angle of the cutting tool edge and in conjunction with the weakening and plastic deformation of the tool subsurface rapidly increases cratering on the tool rake surface.

5 Conclusion and summary

Machining of the Ti6Al4V titanium alloy was carried out at a cutting speed of 150 m/min using an uncoated carbide cutting tool. The mechanisms involved in the formation of a crater on the tool rake surface leading to tool wear were studied. It was found that the three main tool wear mechanisms, viz. adhesion, attrition, and diffusion, existed during the cutting process, which accelerated the tool wear via increasing the depth of the crater on the tool rake surface.

In summary, the following processes[3] are involved during the crater wear of cemented carbide tools when machining titanium alloys:

a) The diffusion interface is formed by adhesion of titanium at the start of the cutting process
b) The tool-chip diffusion boundary varies in thickness across the rake surface of the tool, being thicker near the cutting edge
c) A stable diffusion interface is formed near the cutting edge, followed by an unstable diffusion layer
d) The diffusion of carbon (primarily), tungsten and cobalt (minimal) from the cutting tool surface into the diffusion interface and subsequently in the flowing titanium chips and vice versa
e) Transport of titanium over the surface of the tool-chip diffusion interface, constantly replenishing and adding titanium into the layer
f) Consequent plastic deformation of both the tool-chip interface and the underlying tool, further deteriorating the mechanical and bond strength of the cutting tool
g) A few areas of the unstable diffusion layers cling onto the back surface of the rapidly moving titanium chips
h) The unstable tool-chip interface layers being further abraded by the flowing titanium chips

[3] It should be noted that these processes are not specified in the order of occurrence, as most of these phenomenon are concurrent.

i) A new diffusion interface is formed at places where the previous layer is ruptured by adhesion of the freshly supplied titanium
j) The depth of the crater increases with successive layer reformation and fracture
k) The tool cutting edge fails once it cannot withstand the mechanical stress of the cutting process

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