AN EXPERIMENTAL INVESTIGATION OF ELEMENT DIFFUSION BETWEEN CEMENTED CARBIDE TOOLS AND TITANIUM ALLOYS IN HIGH SPEED MACHINING PROCESSES

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Diffusion wear is one of the main cutting tool wear mechanisms in high-speed machining of hard to machine materials such as titanium alloys. A detailed understanding of this process is very important for improving the cutting tool life and productivity. This work investigated the diffusion of key elements between carbide tool materials and Ti-6Al-4V alloy at different temperatures and times. The element diffusion was analysed using a scanning electron microscope (SEM) and X-ray energy dispersive microanalysis (EDS). Results showed that the elements diffused a longer distance with higher temperatures; however, the diffusion process reached a steady state after a certain diffusion time. The diffusion of the tool materials during the machining process were established from systematic machining tests. The mechanisms of diffusion are discussed in the context of the results obtained.

Keywords: Carbide tool, Ti-6Al-4V, Element diffusion, Diffusion wear.

1. Introduction

Titanium alloys are widely used in the aerospace, automobile, chemical and petroleum industry due to excellent strength-to-weight ratios, high temperature strengths and superior corrosion resistance of the materials [1-3]. Many titanium components are designed with complex geometries and in many cases, a high surface finish requirement, which requires significant amount of machining, such as turning, milling and grinding [4-5]. However, Titanium alloys are difficult to machine because of their low thermal conductivity, high chemical reactivity, low modulus of elasticity and high friction factor compared with many other metal materials [1-6]. High speed machining (HSM) of titanium alloys has

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been a topic of continuing interest for industrial production and scientific research worldwide.

When machining titanium alloys, most cutting tool materials usually exhibit rapid wear. As a consequence, straight cemented carbide tools based on Tungsten Carbide (WC) have been regarded as one of the most practical tool materials available commercially for this application [3, 7]. Many research studies concerned with tool wear mechanisms have established that diffusion wear is one of the main cutting tool wear mechanisms during machining titanium alloys, especially under high cutting speed [7-12]. However, there are only limited numbers of works available concerning this subject. Recently, Deng and Li [13] conducted preliminary research on element diffusion between straight cemented carbide tools and titanium alloys, and it is was noted that prior investigations reported a near 10 times error magnitude concerning the diffusion depth of elements of the diffusion couple due to the age of the inspection instrument. Jiang and Rajiv [14] proposed a cobalt diffusion model to predict crater wear of cutting tools, which showed cobalt diffusion to have a great effect on cutting tool life during cutting titanium alloys. To link the diffusion process directly with the machining process, it is essential to conduct material specific diffusion and cutting tests to further investigate the effect of temperature and time. It is also important to investigate the effect of element diffusion to the property integrality of the tool materials. Both works will provide direct guidance on the cutting parameter selection and cutting tool life optimisation.

In the present study, the effect of temperature and diffusion time on the diffusion of elements between tool material and titanium alloys were examined in detail. The element diffusion was analysed using scanning electron microscopy (SEM) and X-ray energy dispersive microanalysis (EDS). The diffusion wear of both turning and milling cutting tools was analysed in high-speed machining titanium alloys and results correlated to the diffusion tests.

2. Materials and experimental procedures

2.1 Materials

The workpiece material was a typical Ti-6Al-4V alloy, and its composition is listed in Table 1. The workpiece was processed by annealing treatment. The tool material is a Tungsten carbide with cobalt filler (WC/Co), which is commonly used in machining cast iron, nonferrous metal and non-metal materials. The composition, physical, and mechanical properties of this carbide material are listed in Table 2.

Table 1

Chemical composition of Ti–6Al–4V alloy (wt.%)

Element	Al	V	Fe	C	N	O	H	Ti
Content	6.14	4.17	0.10	0.018	0.009	0.11	0.001	Balance

Table 2

Properties of WC/Co carbide tool materials

Composition (wt.%)		WC Grain Size (μm)	Density (g/cm^3)	Hardness (HRA)	Flexural strength (N/mm^2)
94%WC	6% Co	1.0	14.95	92.5	2450

Two different types of experiments were performed: [i] the elements diffusion experiments between carbide tool and titanium alloy and [ii] dry cutting tests of high-speed machining titanium alloys with carbide tools.

2.2 Element diffusion experiments

The diffusion device is shown in Fig. 1. A compressive force generating a pressure of 10MPa was applied to the diffusion couple to obtain a tight contact between the WC/Co carbide tool and the Ti-6Al-4V alloy, which was used to simulate the condition in the actual cutting process. The upper specimen was a carbide tool, while the lower specimen was a Ti-6Al-4V alloy. During preparation, the diffusion couples were heated in an oven at atmospheric pressure for a set length of time and maintained at a specified temperature. The couples were then quickly cooled in air.

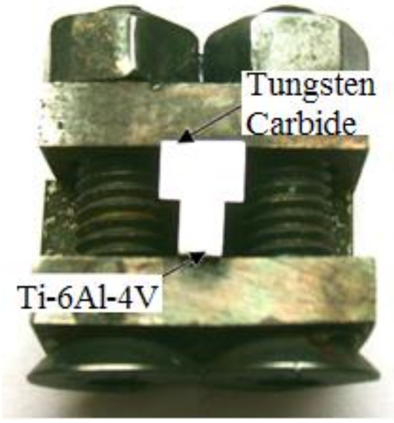


Fig. 1. Diffusion device of tungsten carbide material and titanium alloy

The morphology of the diffusion couples was detected by SEM. EDS was used to analyse the element diffusion between the cutting tool and the Ti alloy through point composition analysis across the interface of the diffusion couples.

2.3 Dry cutting tests

Dry turning test was carried out on a CNC lathe (Type: CA6140). The cutting tool used in the experiment was straight cemented carbide tool (Type: SNMG120408-MS). Cutting tools were inserted into a tool holder (DSSNR2020K12KC04) during the machining process. The workpiece material was in the form of round bar with 100mm diameter. Tests were carried out with the following parameters: cutting speed v=80m/min, feed rate f=0.1mm/r, depth of cut a_p=0.6mm. The criterion of turning was maximum flank wear VB_{max}=0.6mm.

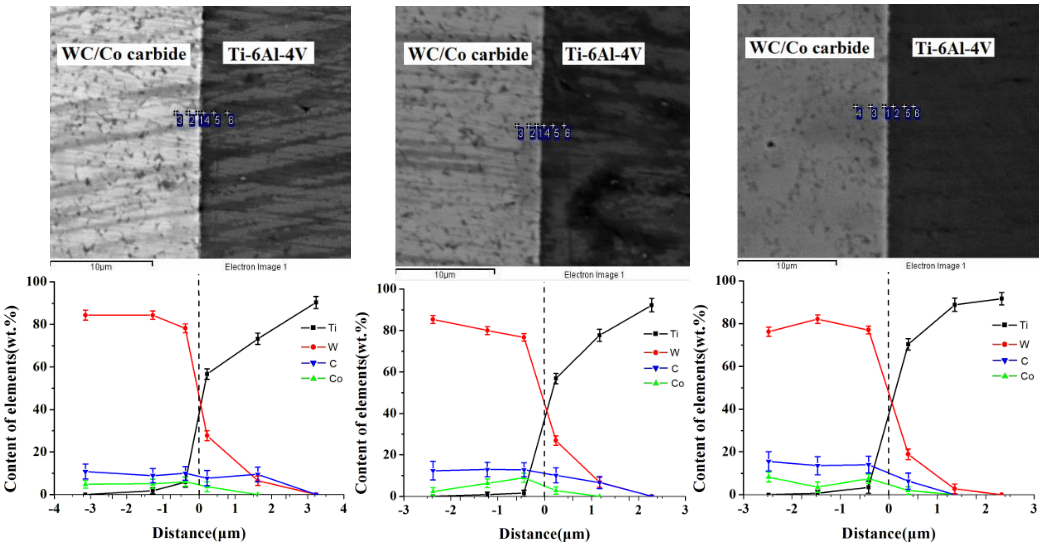
Milling experiments were carried out on a CNC Machining Center (DAEWOO ACE-V500) without cutting fluid. The straight cemented carbide tool used in the test was produced by Zhuzhou Cemented Carbide Works and had the following geometry: axial rake angle γ_p=+5°, radial rake angle γ_f=+5°, clearance angle α_0=+6°. The titanium alloy workpiece was square block of size 100×100×30mm. Tests were carried out by climb milling with the following parameters: cutting speed v=80m/min, feed rate f=0.1mm/r, depth of cut a_p=1mm, a_e=5mm. Cutting length L=5×100mm was the criterion of face milling.

After each cutting test, the wear morphologies of tools were obtained by SEM, and tool diffusion wear was analyzed by EDS.

3. Results and discussion

3.1 Element diffusion at different temperatures

In the cutting process, the main diffusion process involves elements in the tool material diffusing into the titanium alloy, which potentially could cause wear and loss of structure integrity of the tool material, thus influencing its cutting life. Therefore, the study has been focused on the investigation of the diffusion of tungsten (W), carbon (C) and cobalt (Co) elements into the workpiece. The diffusion of the Ti element in the workpiece was also analysed. Fig. 2 illustrates a typical distribution of elements along the interface of the diffusion couple after heating for 90min at different temperatures. The analysis of the diffusion couple for each condition consisted of two parts, the upper part obtained through SEM is the morphology of the diffusion couples, and the other part corresponding to the upper morphology is the distribution curves of elements along the interface. As shown in Fig. 2, there was obvious evidence of the diffusion of W, C and Co elements of the carbide to the Ti-6Al-4V alloy, and Ti of the Ti-6Al-4V alloy to the carbide. The diffusion depth into the Ti-6Al-4V alloy varied among the elements and temperature.



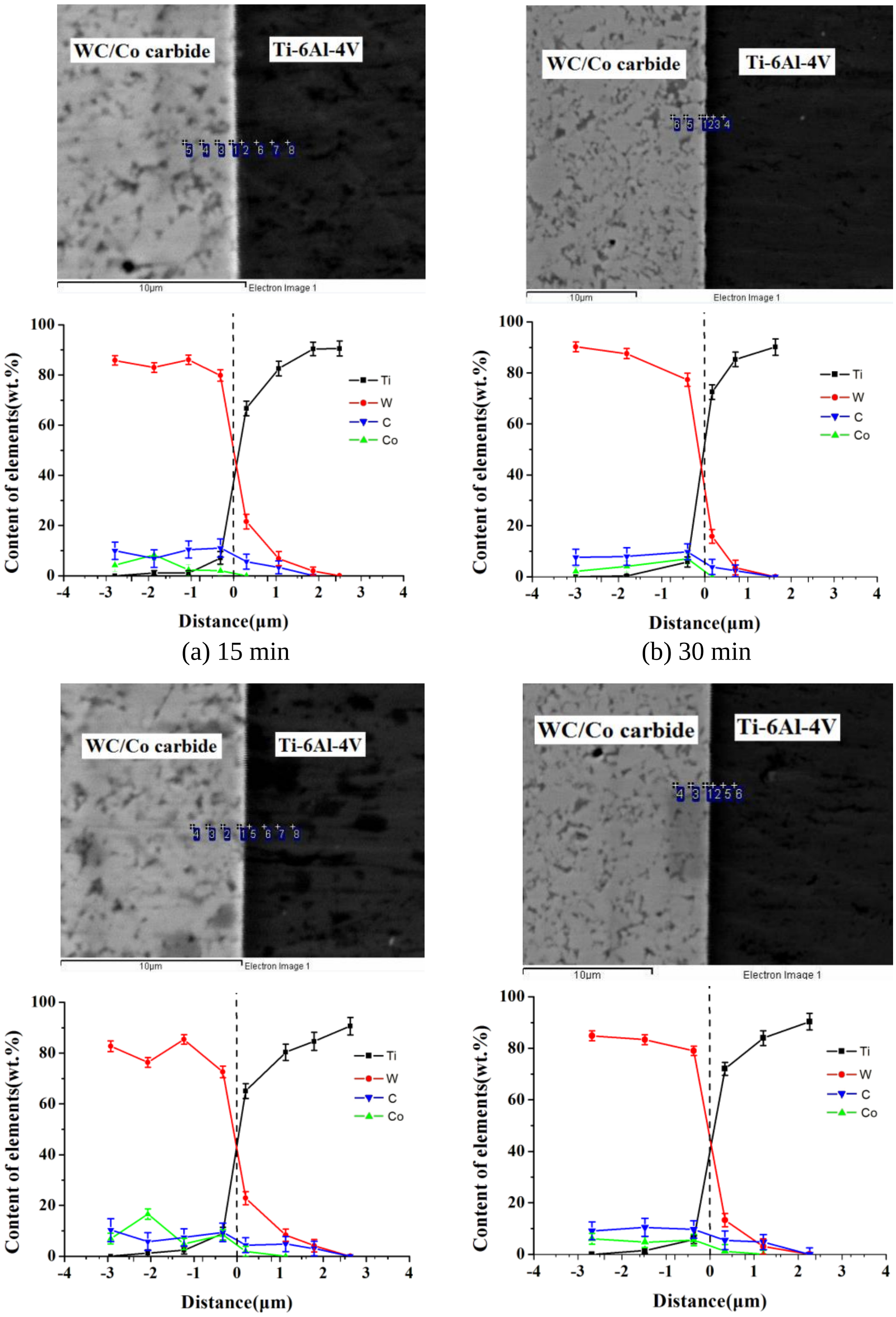
(a) 400 °C (b) 600 °C (c) 800 °C

Fig. 2. Typical elements distribution along the interface of the diffusion couple after heating for 90min at different temperatures

At 400°C, the diffusion depth for the W, C and Co was approximately about 2μm, 1.3μm and under 1μm, respectively. The diffusion depth of the Ti element in the Ti-6Al-4V alloy into the carbide tool was approximately 0.5μm. At 600°C, both W and C elements diffused into Ti-6Al-4V alloy to a depth slightly in excess of 2μm, the Co element penetrated to a depth of approximately 1μm, and Ti element diffused into the carbide tool to a depth of approximately 0.5μm. At a diffusion temperature of 800°C, the diffusion depth of W and C elements to Ti-6Al-4V alloy were approximately 3μm, and the penetration depth of Co element was also up to 1.5μm, and Ti element diffuses to carbide tool more than 1μm. The results clearly indicate that the diffusion depth of elements is related to temperature; higher temperature will cause a deeper diffusion.

3.2 Element diffusion at different diffusion time

Fig. 3 shows the distribution of elements across the interface of the diffusion couple after heating for different times at 600°C, which is common average temperature in machining difficult to machine materials [15, 16]. When the diffusion time is 15 min, the diffusion depth of W and the C elements to the Ti-6Al-4V alloy is approximately 1.5μm, while the diffusion of the Co element was very limited. Fig. 3(c) shows that both W and C elements diffused into the Ti-6Al-4V alloy to a depth of approximately 2μm, the Co element penetrated to a depth of approximately 1μm after 60min heating. At a diffusion time of 180min, the diffusion depth of W, C and Co elements was much deeper. The results also show that the Ti element of the workpiece material had a deeper penetration into the carbide tool with a longer diffusion time.



(a) 15 min (b) 30 min

(c) 60min (d) 180min

Fig. 3. Distribution of elements along the interface of the diffusion couple after heating for different times at 600°C

It is noted that a longer diffusion time will lead to a deeper element penetration, however, the diffusion depth of elements does not have a linear relationship with diffusion time. Fig. 4 shows the maximum diffusion depth of W, C and Co elements with different diffusion times. As shown in Fig. 4, the diffusion depth of W and the C elements had reached up to 1.5μm with a testing time of 15 min. With an increased duration of 60 minutes, the diffusion depth of the W and C elements only increased by approximately 30%. Increasing the heating time to 180 minutes, the diffusion depth of W and the C elements was found to increase slightly. This finding could be significantly important to manage the cutting tool life, further theoretical and computational modeling work is planned to investigate the mechanisms and establish its effect on the cutting tool performances.

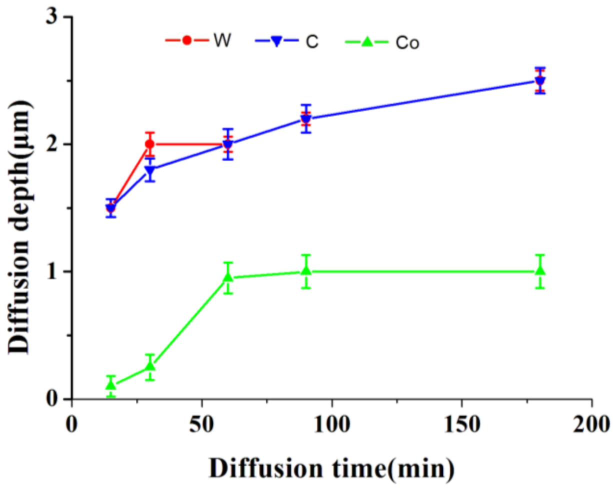
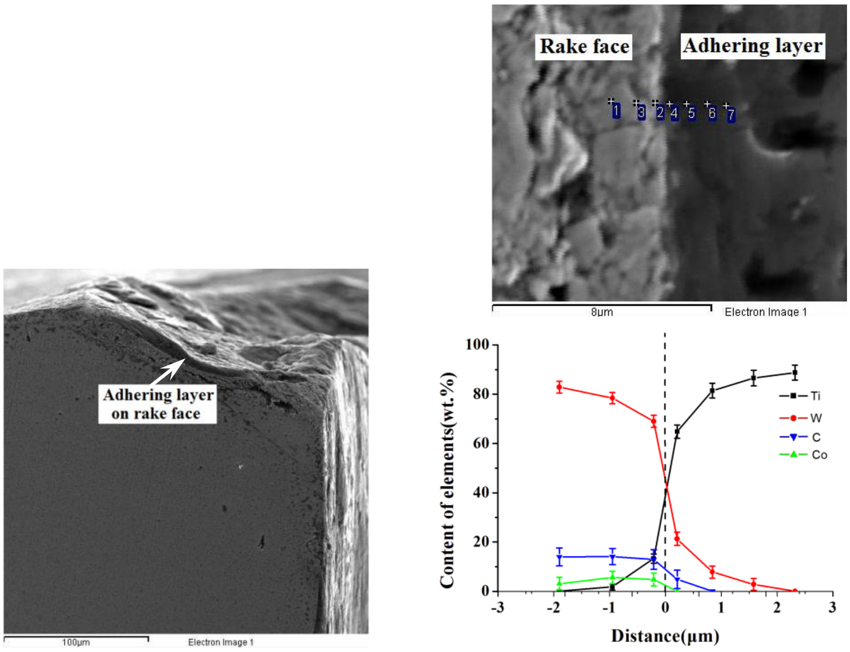


Fig. 4. Maximum diffusion depths of W, C and Co elements with different diffusion time

3.3 Element diffusion of carbide tools in actual cutting process

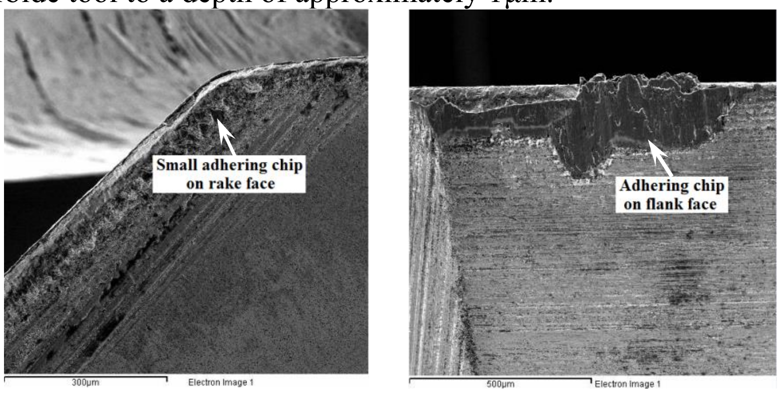
When machining titanium alloys, because of its high chemical reactivity with tool materials, titanium alloys very easily adhere to the cutting tool under the condition of high pressure and high cutting temperature[17]. Element diffusion occurs at the interface of the cutting tool and adhering layer of titanium alloy on tools. Fig. 5 (a) illustrates that there was a clear titanium adhering layer on the rake face through the cross-section micrograph of a turning tool. Fig. 5 (b) illustrates that the W element of the cutting tool diffused into the titanium adhering layer to a depth slightly in excess of 2μm, the C element penetrated to a depth of approximately 0.8μm. Observing the diffusion curve, it is evident that the Co element just began to diffuse, and the Ti element diffused into the carbide tool to a depth of approximately 1μm.



(a) Cross section of turning tool (b) Diffusion curves along the interface

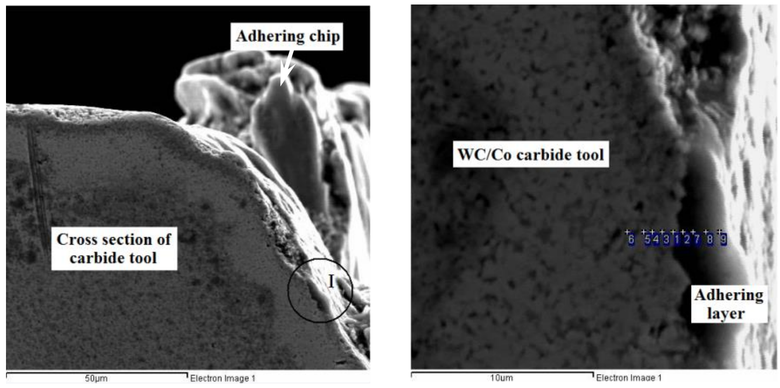
Fig. 5. Distribution of elements along the interface of turning tool and adhering layer on the rake face

Similar test have been performed in milling and the cutting tool wear and element diffusion results were shown in Figures 6 and 7. Although the milling is an interrupted cutting process, we can also find a small adhering chip on the rake face and adhering layer on the flank face as illustrated in Fig. 6. It is shown that the diffusion depth of W element to the titanium adhering layer was in excess of 2μm, the diffusion depth of C element was approximately 1.5μm, while the penetration depth of the Co element was about 0.8μm. The Ti element penetrated into the carbide tool to a depth of approximately 1μm.

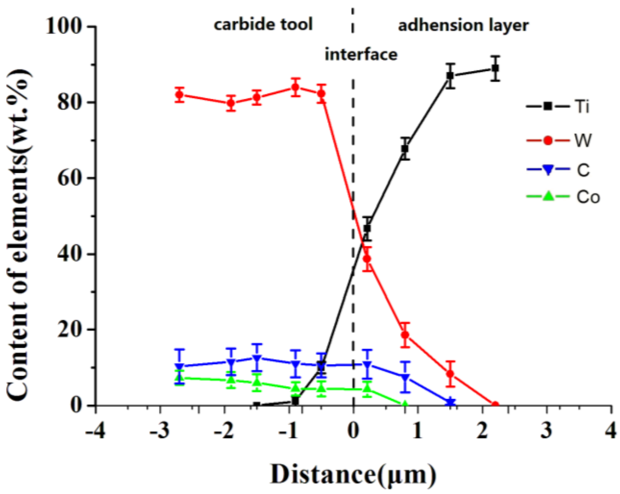


(a) Rake face (b) Flank face

Fig. 6. Typical wear morphologies of milling tool



(a) Cross section of carbide tool (b) Magnified picture of the left I



(c) Diffusion curves corresponding with b

Fig. 7. Distribution of elements along the interface of tool and adhesion layer on the flank face

There is clear evidence that the elements diffusion occurred along the interface of the carbide tool and the titanium adhering layer as shown in Figures 5 and 7. During the cutting process, the element diffusion couple will be formed once the workpiece material adheres to the cutting tool, and the elements of tools will diffuse into adhering layer causing the tool element loss under the high cutting temperature condition. The Ti element of adhering layer will also penetrate into the carbide tool destroying its original structure. When the adhering layer falls from tool surface due to continuous chip flow, one diffusion process finishes, however, another diffusion process will then occur. This cyclical phenomenon may cause serious diffusion wear of cutting tool, reduce tool performance and tool life. It is difficult to directly and exactly quantify the cutting temperature and adhesion time during the cutting process, however, comparing the data in Figures 5 and 7 with Figures 2 and 3, a good deal of similarity was found in the element diffusion curves between stationary diffusion experiments and actual cutting tests. It is therefore reasoned that the diffusion test has potential to help improve understanding of the diffusion process in machining processes and tool wear processes.

4. Conclusions

The element diffusion between WC/Co carbide and Ti-6Al-4V alloy has been examined at different temperatures. There was clear evidence of element diffusion between carbide tools and titanium alloys. The diffusion depth of elements was found to be related to the temperature and diffusion time. Higher temperatures can lead to a deeper diffusion. Longer diffusion time will cause a deeper element penetration; however, the diffusion depth of elements does not have a linear relationship with diffusion time. After a certain diffusion time, the diffusion process reaches a steady state. The diffusion in real cutting processes has also been investigated and the results showed that there is element diffusion between the tool and the adhesion layers in both turning and milling inserts and demonstrated the diffusion wear of carbide tools in the actual cutting process. Future work is required to investigate the diffusion theory to quantitatively describe diffusion tendency, to study diffusion mechanisms to explain why different elements diffuse different distances and to establish their influence on the performance of the cutting tool materials.

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