

Article

Diffusion between Ti6Al4V and Cemented Carbide with Different Compositions

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Abstract: Titanium alloys have been widely used in the aerospace industry because of their excellent properties, such as light weights, high strengths, and corrosion resistance. In this research, the element diffusion between tungsten–cobalt cemented carbide and Ti6Al4V was analyzed using thermodynamic solution theory. First, it was observed that W, Co, and Ti elements diffused under a high temperature and high pressure. Then, by analyzing the diffusion of the different elements, it was found that the amount and depth of the W and Co elements diffusion from the cemented carbide increased with increases in the Co element content and the WC grain size, while the diffusion of the Ti element decreased with increases in the Co element content and decreases in the WC grain size. It was also found that the diffusion amount and depth of the elements increased with increases in the holding temperature and holding time. Finally, the milling experiment was conducted, and an analysis of the cutting-edge section found the existence of Ti in the cemented carbide substrate, which proved the occurrence of the diffusion phenomenon. No Co was found during a chip analysis, but the W element was there. The higher hardness of the WC grains caused the W element to etch onto the chip surface during the milling experiment.

Keywords: Ti6Al4V; endmill; milling; tool materials; diffusion; cemented carbide



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1. Introduction

In recent years, the demand and the performance of aircraft have been increasing with the continuous development of the air cargo, passenger transport, and military industries [1]. Airplanes with higher output efficiencies, better mobility, lower weights, and better fuel utilizations that are greener, more environmentally friendly, and safer are becoming increasingly favored by many, and these demands will continue to promote the application of new materials in aircraft. Titanium alloys are the best choice because of their light weights, high strengths, corrosion resistance, and high-temperature resistance. Titanium alloys have higher strengths than aluminum alloys. Titanium alloys can effectively reduce the weight of aircraft compared with steel [2–4]. However, the excellent performance of the titanium alloys also causes difficulty in its machining. For example, when machining the Ti6Al4V alloy, which is most commonly used in the aviation field, at a high cutting speed, the maximum temperature between the chip and the tool can reach 1000 °C, and cold work hardening easily occurs during machining. This result causes several problems, such as difficulty in improving the material removal rate and insufficient tool life. Cutting titanium alloy with different material tools has attracted wide attention of scholars. As the main tool material used for cutting Ti6Al4V parts, cemented carbide has always been a popular research topic in the aviation industry.

In early research, scholars tried to use tools made from different materials to cut Ti6Al4V. Abbasi et al. used polycrystalline diamond (PCD) tools to mill Ti6Al4V; the results show that the homogeneity of the Ti6Al4V microstructure and the cutting temperature affect

the performance of PCD tools. Uniform microstructures and lower cutting temperatures can prolong the cutting life of PCD tools [5]. Su et al. used PCD tools and polycrystalline cubic boron nitride (PCBN) tools during high-speed milling of a titanium alloy. Analysis of a tool flank using an energy dispersive spectrometer (EDS) shows that PCD tools have longer cutting lives than PCBN tools. Especially during high-speed cutting, PCBN tools experience oxidation wear during machining, which seriously affects the tool life [6]. Zareena et al. obtained a higher surface machining quality using single-crystal diamond tools for ultra-precision machining of titanium alloys. They found that using a perfluoropolyether (PFPE) coating on the substrate of single-crystal diamond (MCD) tools can effectively reduce material adhesion and friction and further improve the surface processing quality and tool life [7]. Zhang et al. used Si₃N₄ ceramic tools to mill titanium alloys at high speeds and analyzed the machinability of the tool flank face wear. The results showed that tool failure occurred primarily because of wear. They also obtained a better surface processing quality, which could be used during machining of titanium alloys [8].

Although scholars have fully analyzed the performance of different tool materials during the machining of titanium alloys, cemented carbide tools are still the primary cutting tools. According to chemical composition and use characteristics, cemented carbide can be divided into four categories: tungsten cobalt (WC+Co), tungsten titanium cobalt (WC+TiC+Co), rare metal carbide (WC+TiC+TaC/NbC+Co), and titanium carbide-based (WC+TiC+Ni+Mo) cemented carbide. Li et al. used titanium carbide-based cutting tools to cut titanium alloys, finding that diffusion occurred in the tool wear region, thereby reducing the cutting life [9]. Li et al. observed the diffusion phenomenon when cutting Ti6Al4V with tungsten–cobalt–titanium–cemented carbide. The tool had serious adhesion, diffusion, and oxidation wear. Under high-temperature conditions, W and Co elements penetrate into Ti6Al4V, while Ti elements penetrate in the cemented carbide direction. Element diffusion reduces the tool hardness and the tool life, but tungsten–cobalt cemented carbide tools have lower diffusion rates than titanium-based cemented carbide tools. It can effectively ensure the wear resistance of the cutting tool [10–12]. At the same time, a similar phenomenon was found in Yang’s research [13]. Kuczmazewski et al. analyzed the influence of the WC grain size of tungsten cemented carbide on the cutting performance when cutting a titanium alloy. Compared with coarse-grain and fine-grain bars, tools made of ultra-fine-grain bars have excellent wear resistance and better surface processing quality [14]. Liu et al. analyzed the effect of tungsten–cobalt carbide on the cutting performance of Ti6Al4V under different flank wear and cooling conditions, and found that the element diffusion increased with the increase in flank wear. Compared with dry cutting and cutting under coolant conditions, a low-temperature auxiliary chip can effectively improve tool life and inhibit element diffusion [15]. Olander et al. carried out Ti6Al4V turning test with tungsten–cobalt carbide inserts, and detected the wear area. It was found that the C element in WC grains was seriously lost, forming a W rich zone [16]. Lindvall et al. also conducted Ti6Al4V turning test, and found no W rich area in the wear area, but found the existence of W element on the machined surface. At the same time, the C poor WC grain interacted with Co element to form Co₃W, and the Co rich area at the tool-chip contact interface formed TiCo₂, which can effectively delay the further occurrence of element diffusion [17]. Wang et al. found that the addition of rare metal carbides, such as TaC, NbC, Cr₃C₂, and VC, in ultra-fine-grain cemented carbide materials can improve the density, inhibit abnormal grain growth, effectively improve the high-temperature hardness and strength of the tools, and reduce tool wear during titanium alloy cutting [18]. Zhou et al. prepared ultra-fine gradient cemented carbide tools with different gradient layer thicknesses by adjusting the Co and Ti contents; they emphasized that Co₁₀Ti₃ substrate material performed best during high-speed titanium alloy milling [19].

In this study, the influence of diffusion wear on the life of Ti6Al4V cutting tools is analyzed in detail, which provides guidance for the design of tool life extension. The solubilities of W, Co, and Ti elements at different temperatures were first obtained through calculations, and the trends of diffusion between elements as functions of temperature

were analyzed. Second, an experiment was conducted to analyze the diffusion trends for the WC grain size and the Co element content at different temperatures and different holding times to provide guidance for the selection of cemented carbide materials to inhibit diffusion. Finally, solid carbide endmills were prepared for a cutting experiment to verify the diffusion trends, and the results can provide guidance for the selection of tool materials for Ti6Al4V cutting.

2. Diffusion Based on Thermodynamic Solution Theory

2.1. Diffusion Based on Thermodynamic Solution Theory

Gibbs free energy, also known as free enthalpy or free energy, refers to the portion of internal energy reduced by the system that can be converted into external work during a thermodynamic process. It can be expressed by Equation (1):

$$G = U + pV - TS \quad (1)$$

where G represents the Gibbs free energy (J/mol), U is the internal energy (J/mol), p is the pressure (Pa), V is the volume (mm^3), T is the temperature (K), and S represents the entropy (J/(mol·K)).

ΔG represents a change in the free energy and it is used to evaluate whether a reaction or change can occur spontaneously under constant temperature and pressure conditions. When $\Delta G < 0$, the process can occur spontaneously, when $\Delta G = 0$, the process is in balance, and when $\Delta G > 0$, the process cannot be spontaneous.

Assuming that the tool material is $A_xB_yC_z$, the free energy generated by the tool material can be expressed by Equation (2):

$$\Delta G_{A_xB_yC_z} = x\Delta\bar{G}_A + y\Delta\bar{G}_B + z\Delta\bar{G}_C \quad (2)$$

In Equation (2), $\Delta G_{A_xB_yC_z}$ is the free energy generated when the tool material $A_xB_yC_z$ dissolves between the tool and the workpiece at a certain temperature. $\Delta\bar{G}_i$ ($i = A, B, C$) represents the relative partial molar free energy of the solid solution formed by elements in the tool material and the workpiece. Equation (3) can be obtained from the laws of thermodynamics:

$$\Delta\bar{G}_i = \Delta\bar{G}_i^R + RT \ln C_i \quad (3)$$

where $\Delta\bar{G}_i^R$ ($i = A, B, C$) represents the excess free energy in the solid solution formed by elements in the tool material and the workpiece, C_i ($i = A, B, C$) is the dissolved concentration of tool elements in the workpiece, and R is the gas constant, which is approximately equal to 8.314 J/mol·K.

By integrating Equations (2) and (3), the solubility of the available tool material in the workpiece can be obtained, as shown in Equation (4):

$$C_{A_xB_yC_z} = \exp \left(\frac{\Delta G_{A_xB_yC_z} - \Delta\bar{G}^R - RTM}{NRT} \right) \quad (4)$$

In Equation (4), $C_{A_xB_yC_z}$ represents the solubility of the tool material in the workpiece, and M and N can be expressed by $M = x \ln x + y \ln y + z \ln z$ and $N = x + y + z$. It was found that $M = 0$ and $N = 2$ for WC material. In addition, $\Delta\bar{G}^R$ is the excess free energy formed by the W and C elements after contact with the Ti6Al4V. Therefore, $\Delta\bar{G}^R$ can be expressed by Equation (5):

$$\Delta\bar{G}^R = \Delta\bar{G}_W^R + \Delta\bar{G}_C^R \quad (5)$$

The solubility of the tool material in the titanium alloy can be obtained by knowing the free energy of the tool material formation at different temperatures, as well as the excess free energy of each tool material component when forming a solid solution in the workpiece material.

2.2. Calculation of the Tool Material Solubility in Ti

The primary component in tungsten–cobalt cemented carbide tools is WC. The free energy generated by the WC material at different temperatures can be obtained by the Gibbs free energy function method, as shown in Table 1.

Table 1. Free energy generated by the WC material at different temperatures.

T/K	400	600	800	920	1000	1200	1400
$\Delta G_{WC}/J$	−37,700	−36,886	−36,287	−35,891	−35,777	−35,307	−34,853

Tungsten–cobalt cemented carbide tools are primarily composed of W, C, and Co elements. The solubility of C in Ti is approximately 0.95% when the temperature is 1200 K, and the free energy of formation for the WC material is −35,307 J [20]. Substituting this information into Equation (4) generated the excess free energy value of C formed in the titanium alloy, $\Delta \bar{G}_C^R$, of 57,606 J.

The solubility of W in Ti is 28%, and the free energy of formation for WC is −35,777 J when the temperature is 1000 K [21]. Substituting this information into Equation (4) generated the excess free energy value of W formed in the titanium alloy $\Delta \bar{G}_W^R$ of −10,376 J.

By introducing $\Delta \bar{G}_W^R$ and $\Delta \bar{G}_C^R$ into Equation (3), the excess free energy of the WC material in the titanium alloy was calculated to be 47,230 J. Combining this with Equation (4) obtained the solubility of WC in Ti at different temperatures, as shown in Table 2.

Table 2. Solubility of WC in Ti at different temperatures.

T/K	400	600	800	920	1000	1200
$C_{WC}/\%$	0.00092	0.02	0.18	0.44	0.68	1.6

The solubility of the Co element in Ti can be directly obtained from the binary alloy phase diagram of Co and Ti, as shown in Figure 1. The solubility of Co in Ti at different temperatures is shown in Table 3. With increases in the temperature, the solubility of Co in Ti also increases.

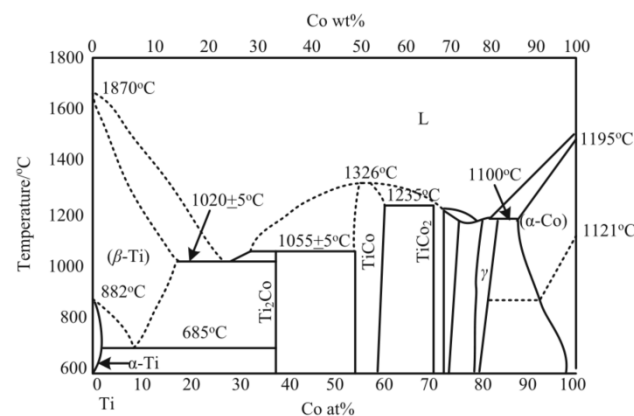


Figure 1. Ti–Co binary alloy phase diagram data from [22,23].

Table 3. Solubility of Co in Ti at different temperatures.

T/K	800	900	1000	1200
$C_{Co}/\%$	3	4	4.5	8

When diffusion occurs during cutting, the hardness of the tool material is reduced, which leads to insufficient tool wear resistance and premature tool failure. Through the

analysis of the diffusion mechanism during cutting, the wear resistance of cutting tools can be effectively improved. It was found during this study that the solubility of WC and Co in titanium alloys increases with increases in the temperature.

3. Experimental Details

A variety of different experiments were carried out. First, the basic experiment of element diffusion was carried out to simulate the contact process of cutting Ti6Al4V by cemented carbide. The method of pressing plate and bolt was used to make the cemented carbide material with WC grain sizes and Co contents contact Ti6Al4V under constant pressure and put it into the holding furnace. The holding furnace model was Bona BR-14AS-27. By controlling the holding temperature and holding time, the sample after the holding test was put into the resin insert. Conduct section treatment, and verify whether there is element diffusion under high temperature conditions through EDS of scanning electron microscope (SEM), and the influence of WC grain size, Co content, holding time, and holding temperature on element diffusion. The SEM model is ZEISS EVO-18. Select face scanning and set the scanning area to $0.3\ \mu\text{m} \times 0.3\ \mu\text{m}$. Take the average scanning value of this area. Subsequently, Walter Helitronic Power equipment was used to grind different components of cemented carbide materials into integral cemented carbide endmills and conduct Ti6Al4V milling experiments. The worn cutting edges and chips were analyzed by EDS.

3.1. Diffusion Experiment

In the diffusion experiment, cemented carbide materials with different compositions that were 5 mm in length and 6 mm in diameter were clamped to Ti6Al4V materials under a certain pressure. The clamping force was controlled at 80 N·m using a torque wrench, and the pressure was approximately 2.86 MPa. The contact surfaces were polished. The surface roughness Ra value measured by hand-held roughness measuring instrument can reach $0.05\ \mu\text{m}$. Finally, the clamped workpieces were placed into the holding furnace for the experiment. The holding temperature was maintained at 400 °C, 600 °C, and 800 °C for 30, 60, and 90 min, respectively. The orthogonal scheme for the element diffusion experiment is shown in Table 4. A schematic diagram of the element diffusion experiment is shown in Figure 2. Subsequently, phenolic resin was used to insert the workpiece after the experiment. The accuracy of the experiment was ensured by grinding and polishing the side. An EDS analysis of the Ti6Al4V and the cemented carbide on the polished surfaces was performed using a SEM. The Ti6Al4V was primarily composed of Ti, as well as small amounts of Al (5.5–6.75%) and V (3.5–4.5%). The properties of the Ti6Al4V are shown in Table 5. Materials from Jiangsu Tiangong International Co., Ltd. The properties and compositions of the cemented carbide materials with different compositions are shown in Table 6. The surfaces of the cemented carbide samples were polished with a diamond polishing agent on a polishing machine, then the polished surfaces were etched at room temperature for 20 s with a mixture of 20% (by weight) potassium ferricyanide and sodium hydroxide. Then they were placed into ethanol for ultrasonic cleaning so that the microstructures of the cemented carbide materials with different components could be obtained. Figure 3 shows that the Co phase was evenly distributed in five cemented carbide samples and that the abnormal growth of WC grains was not obvious. In addition, the edges of the WC grains flattened obviously, and there were equilibrated WC grains with triangular or triangular cross sections that were well developed.

Table 4. Orthogonal scheme for the element diffusion experiment.

No.	Temperature (°C)	Holding Time (min)	Brand
1	600	60	C0406
2	400	60	C0406
3	800	60	C0406
4	600	30	C0406
5	600	90	C0406
6	600	60	C0410
7	600	60	C0412
8	600	60	C0206
9	600	60	C0806

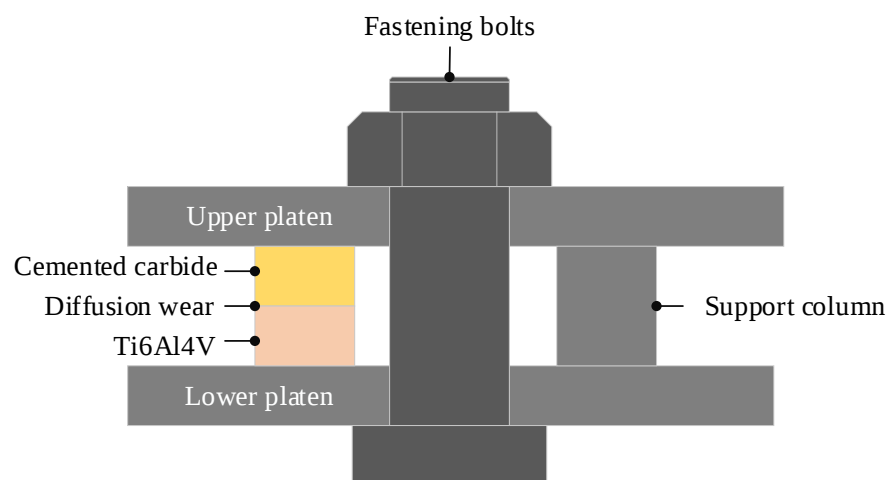
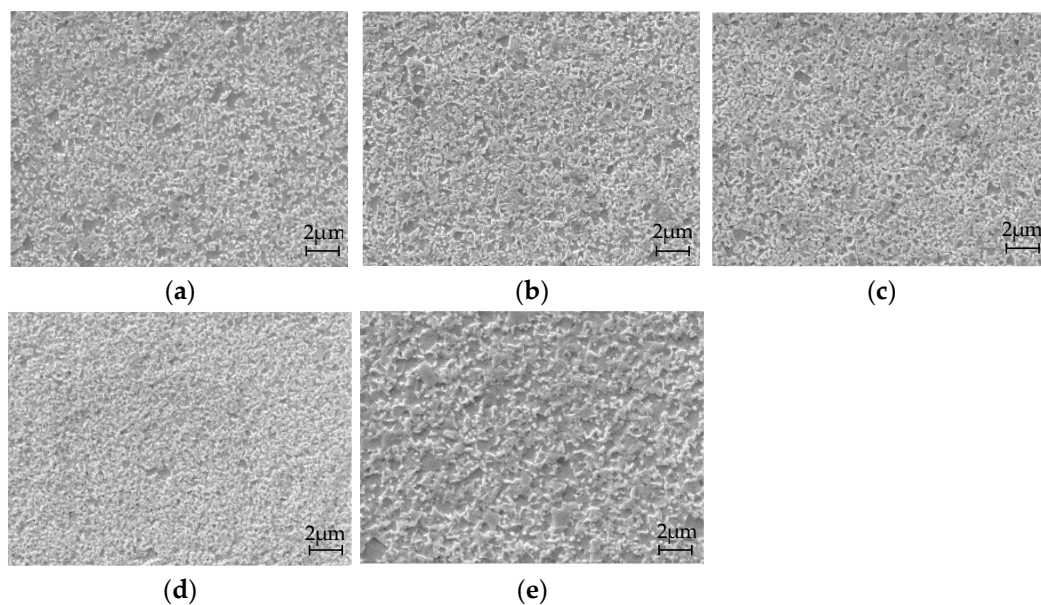
**Figure 2.** Schematic diagram of the element diffusion experiment.**Figure 3.** SEM images of the cemented carbide samples. (a) C0406; (b) C0410; (c) C0412; (d) C0206; (e) C0806.

Table 5. Properties of the Ti6Al4V.

Density (g/cm ³)	Hardness (HRA)	Young's Modulus (GPa)	Thermal Conductivity (W/(m·K))	Coefficient of Thermal Expansion ($\times 10^{-6}/\text{K}$)
4.44	68	112.0	5.44	8.53

Table 6. Properties and compositions of the cemented carbide samples.

Brand	WC Grain Size (μm)	Co Content (%)	Hardness (HRA)	Bending Strength (N/mm ²)	Density (g/cm ³)
C0406	0.4	6%	94	3800	14.8
C0410	0.4	10.30%	91.7	3500	14.4
C0412	0.4	12%	92.6	4200	14.1
C0206	0.2	6%	94.6	3800	14.7
C0806	0.8	6%	93	2700	14.83

3.2. Milling Experiment

An endmill that used cemented carbide materials with different compositions was prepared. Geometric parameters of the endmill are shown in Table 7. Cutting parameters for the milling are shown in Table 8. The milling experiment, which was performed with a CAMPIO CNV-900 high-speed machine, is shown in Figure 4. Water-based emulsion cooling was used during the experiment.

Table 7. Geometric parameters of the endmill.

Diameter (mm).	Number of Blades (-)	Helix Angle ($^{\circ}$)	Rake Angle ($^{\circ}$)	Flank Angle ($^{\circ}$)	Blade Width (mm)
6	4	38–40	5	10	0.45

Table 8. Cutting parameters.

Milling Method	v (mm/min)	f (mm/z)	ae (mm)	ap (mm)	Milling Length (mm)
Side milling	80	0.05	0.5	4	400

**Figure 4.** Milling experiment.

4. Results and Discussion

4.1. Element Diffusion between Materials

When milling Ti6Al4V with cemented carbide tools, the W, Co, and C elements in the tools diffuse in the Ti6Al4V direction under high temperatures and pressures, and the Ti elements in the Ti6Al4V diffuse in the cemented carbide direction. The diffusion of elements reduces the tool hardness and affects the cutting lives of the tools. Figure 5 shows the distribution of the element diffusion interface after holding at 600 $^{\circ}\text{C}$ for 60 min.

SEM images for the C0406 and the Ti6Al4V are shown in Figure 5a and diffusion curves are shown in Figure 5b. Point 0 on the horizontal axis represents the diffusion interface between the cemented carbide and the Ti6Al4V. Under high-temperature and high-pressure conditions, diffusion occurs between the W, Co, C, and Ti elements. In this experiment, the diffusion depth of the W, Co, and C elements from the cemented carbide was approximately 3 μm . The diffusion depth of the Ti element from the Ti6Al4V was less than 1 μm . At 0.5 μm in the Ti6Al4V direction, the diffusion amount of the W element was 30.79%, and the diffusion amount of the Co element was 1.25%, which is far greater than the solubility at the same temperature. This result indicates that a chemical reaction between the W and Co elements took place under high-temperature conditions, resulting in new phases.

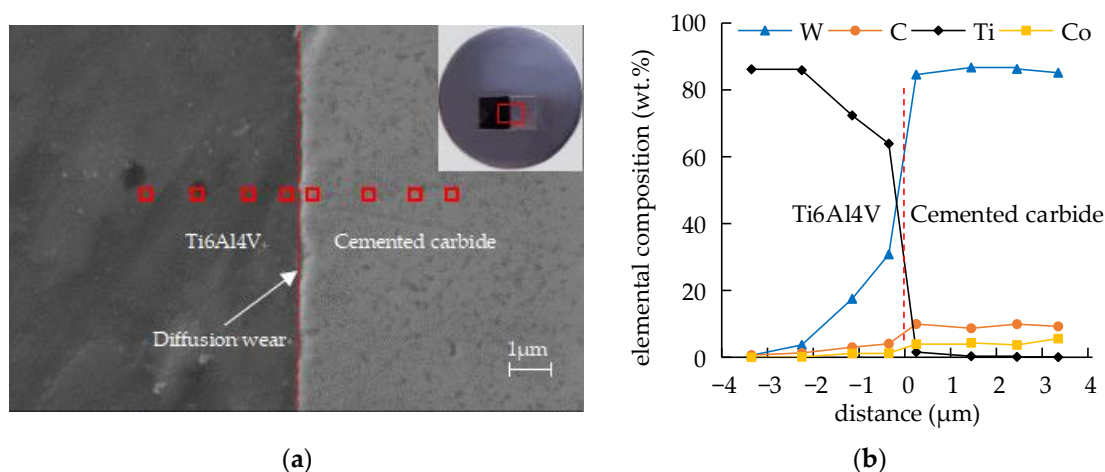


Figure 5. Element diffusion after 60 min of heating at 600 $^{\circ}\text{C}$. (a) SEM images for the C0406 and the Ti6Al4V; (b) Diffusion curves for the C0406 and the Ti6Al4V.

4.2. Influence of Element Content on Diffusion

Next, three groups of experimental data from Table 4, groups No. 1, No. 6, and No. 7, were compared. Diffusion between the cemented carbide samples with different element contents and the Ti6Al4V was analyzed for a holding temperature of 600 $^{\circ}\text{C}$ and a holding time of 60 min, as shown in Figure 6.

Diffusion of the Co element is shown in Figure 6a. For the same diffusion depth, the amount of the Co element diffused in the Ti6Al4V increased with increases in the Co element content. The diffusion depth also increased with increases in the Co element content. However, it is worth noting that the content of the Co element in the cemented carbide fluctuated; this phenomenon may have occurred because the WC grains were preferentially removed during the polishing process when a Co element in the cemented carbide was used as the adhesive, leading to non-uniformity in the Co content.

Diffusion of the W element is shown in Figure 6b. The diffusion depth was approximately 3 μm . A comparison of C0406 with C0410 and C0412 shows that the amount of the W element diffused increased with increases in the W element content.

Diffusion of the Ti element is shown in Figure 6c, in which C0406 is compared with C0410 and C0412. An analysis of the Ti element diffusion from the Ti6Al4V toward the cemented carbide shows that the diffusion depth and amount of the Ti element decreased with increases in the Co element content. The homogeneity of the cemented carbide materials increased with increases in the Co element content, which reduced the number of internal defects in the material and effectively inhibited the diffusion of the Ti element toward the cemented carbide.

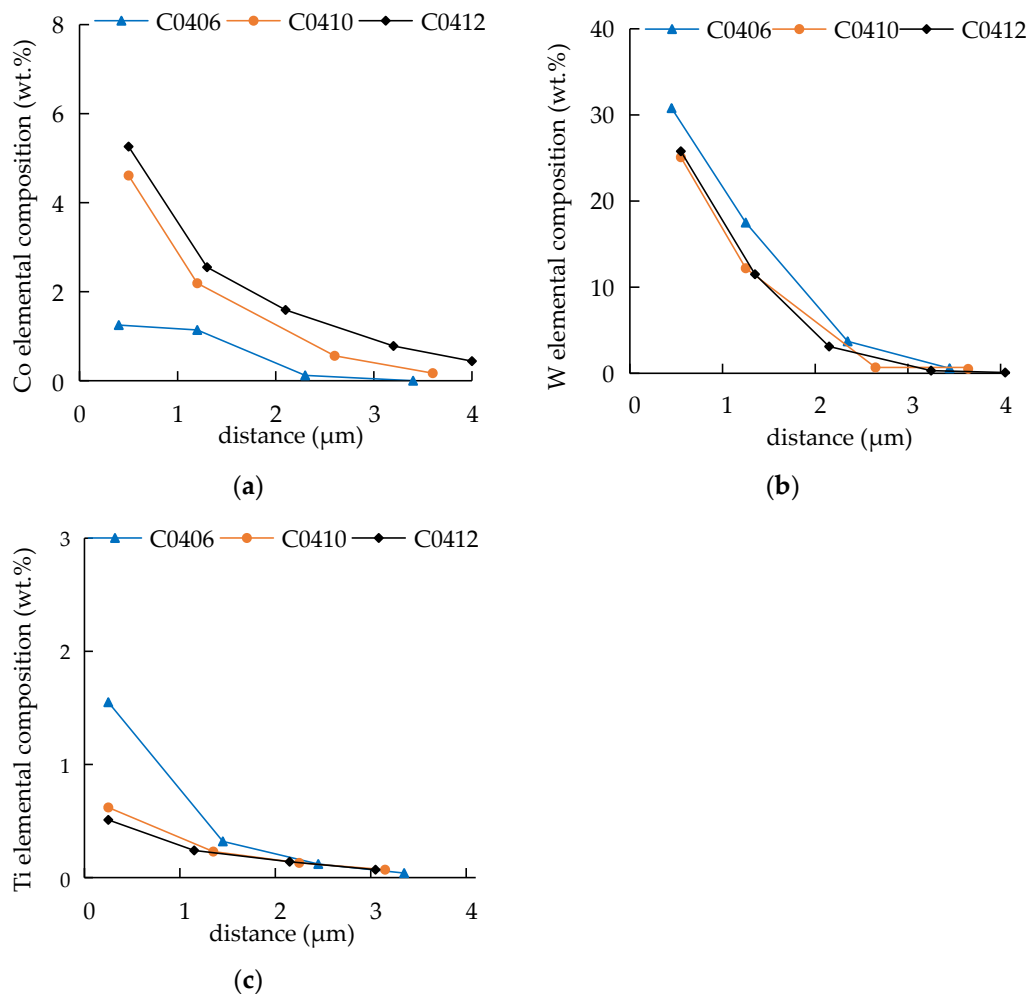


Figure 6. Diffusion between cemented carbide samples with different element contents and the Ti6Al4V. (a) Diffusion of the Co element; (b) Diffusion of the W element; (c) Diffusion of the Ti element.

4.3. Influence of WC Grain Size on Diffusion

By comparing three groups of experimental from data Table 4, groups No. 1, No. 8, and No. 9, as shown in Figure 7, the diffusion between the cemented carbide samples with different WC grain sizes and the Ti6Al4V was analyzed for the same temperature, holding time, and Co content.

Diffusion of the W element is shown in Figure 7a. The amount of the W element diffused in the direction of the Ti6Al4V increased with increases in the WC grain size, which had little effect on the diffusion depth of the W element. However, for the same depth, the diffusion depth of the elements increased with increases in the diffusion amount. The diffusion amount and depth of the W element increased with increases in the WC grain size.

Diffusion of the Co element is shown in Figure 7b. For the same diffusion depth in the Ti6Al4V region, within 2 μm, the amount of the Co element diffused increased with increases in the WC grain size. This result occurred because with increases in the WC grain size, it was easier to peel off the WC grains when polishing the contact surfaces, leading to increases in the Co element content. With increases in the Co element content, both the diffusion amount and depth show increasing trends.

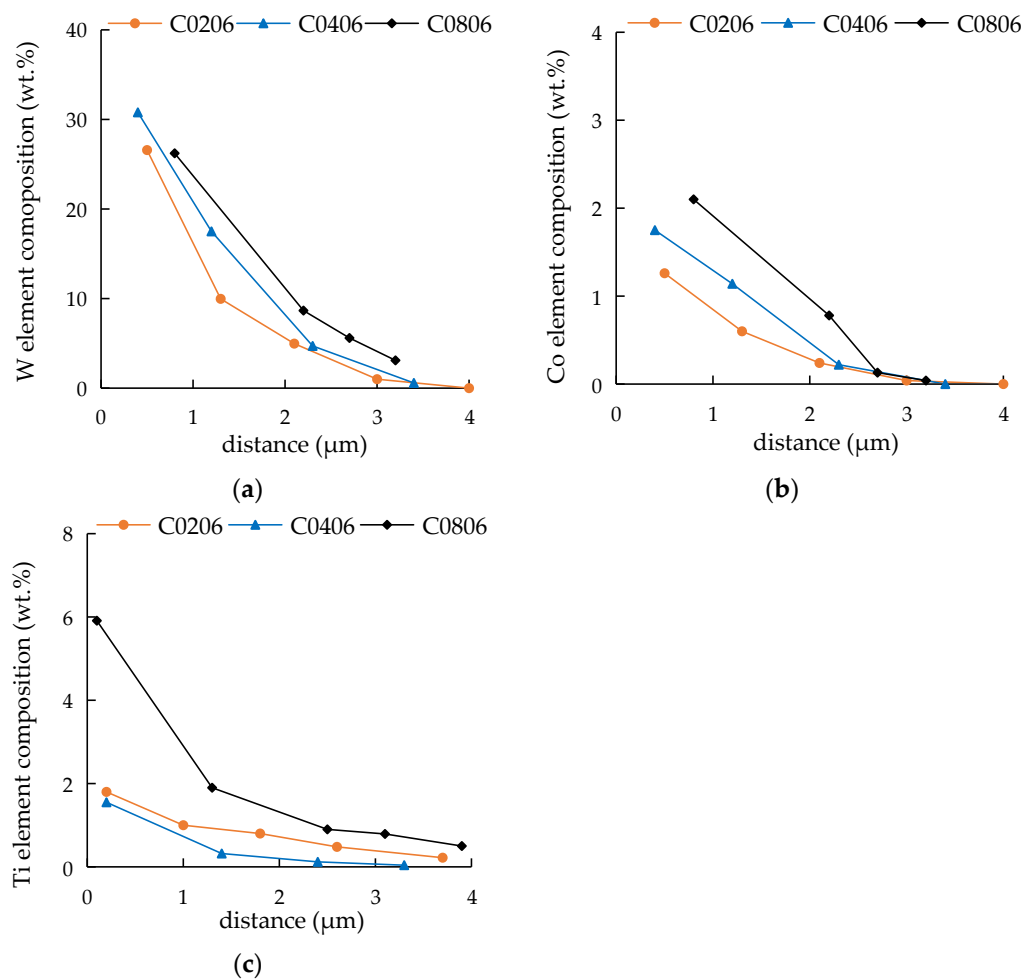


Figure 7. Diffusion between the cemented carbide samples with different WC grain sizes and the Ti6Al4V. (a) Diffusion of the W element; (b) Diffusion of the Co element; (c) Diffusion of the Ti element.

Diffusion of the Ti element is shown in Figure 7c. A comparison of C0806 with C0406 and C0206 shows that the initial amount of the Ti element diffused also increased with increases in the WC grain size. This result occurred because the homogeneity of the cemented carbide material increased with the refinement of the WC grain size, which effectively prevented diffusion of the elements. Meanwhile, increases in the diffusion of Ti toward the cemented carbide also caused increases in the amounts of W and Co diffused toward the Ti6Al4V.

4.4. Influence of Temperature on Diffusion

By comparing experimental data from groups No. 1, No. 2, and No. 3 from Table 4, the element diffusion between the C0406 cemented carbide and the Ti6Al4V was analyzed for the same holding time and different holding temperatures, as shown in Figure 8.

Diffusion of the W element is shown in Figure 8a. The amount and depth of the W element diffused increased with increases in the temperature. In the Ti6Al4V direction at approximately 1 μm, the amount of the W element diffused at 400 °C was far lower than that diffused at 600 °C and 800 °C. In the cemented carbide direction at approximately 1 μm, the loss rate of the W element was higher at an 800 °C holding temperature, and the contents of the W element were equivalent at 400 °C and 600 °C. The amount and depth of the W element diffused accelerated with increases in the holding temperature. When the temperature reached 800 °C, the diffusion of the W element increased rapidly.

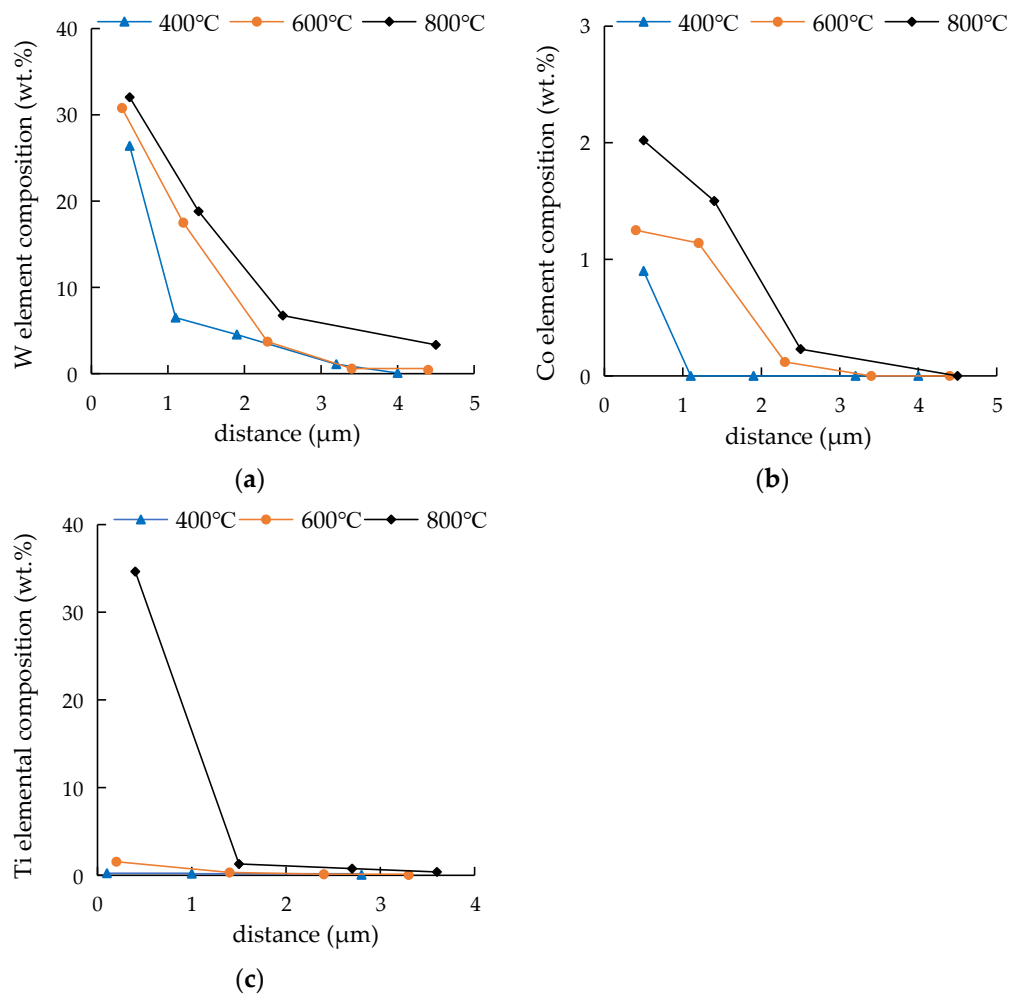


Figure 8. Element diffusion between the cemented carbide and the Ti6Al4V at different holding temperatures. (a) Diffusion of the W element; (b) Diffusion of the Co element; (c) Diffusion of the Ti element.

Diffusion of the Co element is shown in Figure 8b. In the Ti6Al4V direction, the diffusion of the Co element was equivalent to that of the W element, and the amount and depth of the element diffusion increased with increases in the temperature. At 400 °C, the depth of the Co element diffused toward the Ti6Al4V was approximately 1 μm. At 600 °C and 800 °C, the depth of the Co element diffused toward the Ti6Al4V was approximately 2.5 μm. When the temperature was 800 °C, the Co element loss in the cemented carbide direction was high, and the diffusion also increased rapidly.

Diffusion of the Ti element is shown in Figure 8c. The depth of the Ti element diffused toward the cemented carbide was less than 1 μm when the holding temperature was 400 °C and 600 °C. The diffusion depth was greater than 1 μm at 800 °C. This result shows that the depth and amount of the Ti element diffused toward the cemented carbide increased with increases in the holding temperature.

It is worth noting that when the temperature was kept at 800 °C for 30 min, an obvious oxide layer appeared on the surface; this oxide layer was brittle, and some of it had peeled off, as shown in Figure 9. This occurred because, at high temperatures, WC and Co elements exposed to air undergo oxidation reactions and are oxidized to form WO_3 and Co_3O_4 , respectively [10].

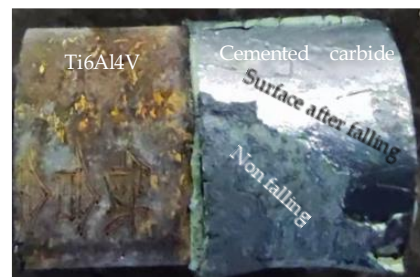


Figure 9. Oxidation analysis of the cemented carbide at 800 °C.

4.5. Influence of Holding Time on Diffusion

By comparing three groups of experimental data from Table 4, groups No. 1, No. 4, and No. 5, the element diffusion between the C0406 cemented carbide and the Ti6Al4V was analyzed for the same holding temperature and different holding times, as shown in Figure 10.

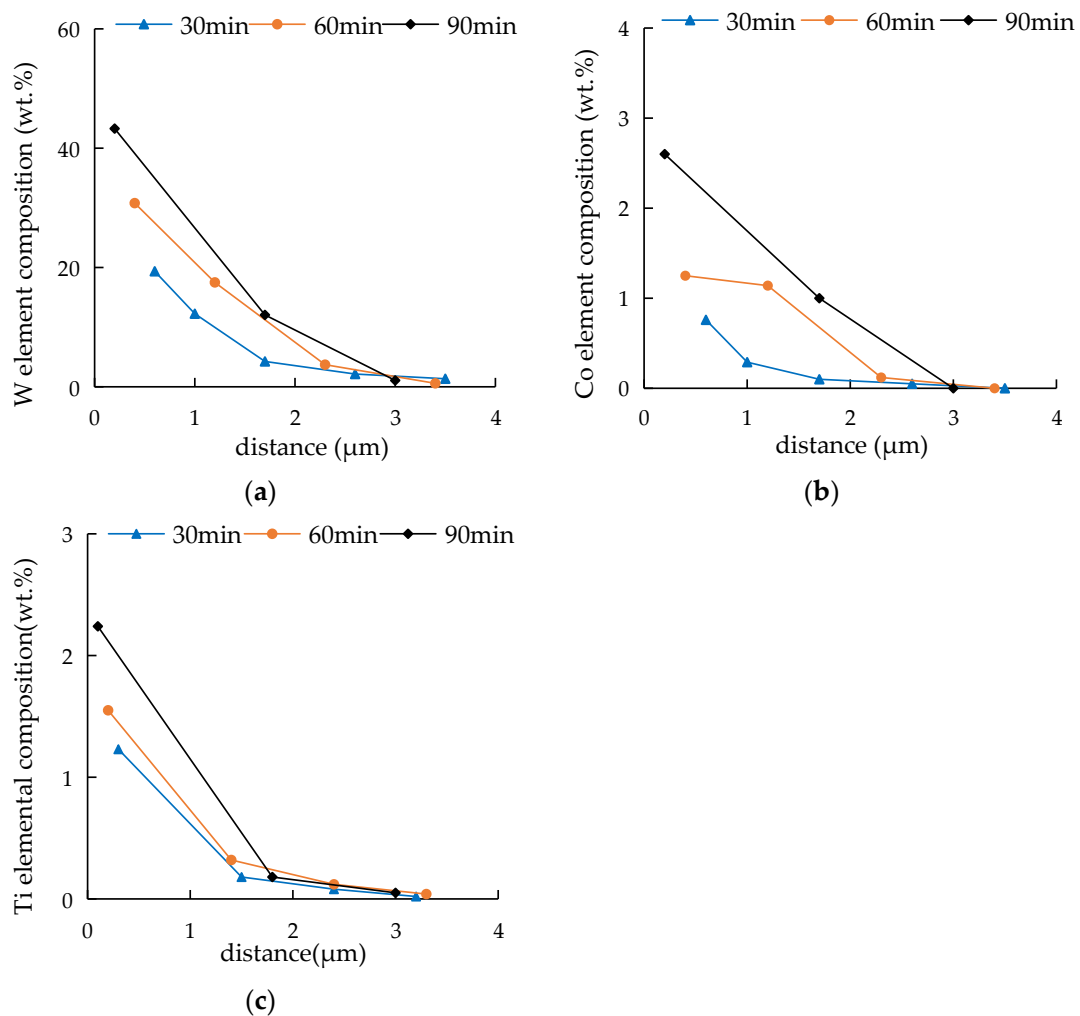


Figure 10. Element diffusion between the cemented carbide and the Ti6Al4V for different holding times. (a) Diffusion of the W element; (b) Diffusion of the Co element; (c) Diffusion of the Ti element.

Diffusion of the W element is shown in Figure 10a. The amount of the W element diffused increased with increases in the holding time, but the diffusion depth, approximately 3 μm, did not change significantly. Comparing the results for 30 min with those for 60 and

90 min shows that the diffusion amount increased obviously when the holding time was 60 or 90 min.

Diffusion of the Co element is shown in Figure 10b. The amount of the Co element diffused increased with increases in the holding temperature. Comparing the results for 30 min with those for 60 and 90 min shows that the diffusion depth was only approximately 1 μm when the holding time was 30 min. This result proves that the diffusion depth increased with increases in the holding time.

Diffusion of the Ti element is shown in Figure 10c. The amount of the Ti element diffused in the cemented carbide direction increased with increases in the holding time. However, the holding time had little effect on the diffusion depth.

4.6. Milling Experiment

A Ti6Al4V milling experiment was performed using cemented carbide tools made of the five cemented carbide materials described above, and the influences of the cemented carbide components on the element diffusion were analyzed. The cutting parts perpendicular to the axial direction were cut off and embedded in phenolic resin, and then the surfaces were polished, cleaned with alcohol, and placed into the SEM for EDS analysis of the element content changes on the worn edge, as shown in Figure 11. An SEM image of the cutting edge is shown in Figure 11a, and the element diffusion curve along the wear area is shown in Figure 11b. On the left side of point 0 is the area not involved in cutting, and on the right side of point 0 is the wear area. The Figure shows that the content of the W element in the wear area decreased and the content of the Co element increased. This happened because friction wear occurred during the cutting process, WC grains peeled off, and the remaining adhesive Co remained on the edge surface. The Ti element was detected in the wear area of the cutting edge, and it adhered to the wear area of the cutting edge. The diffusion depth of the Ti element was less than 3 μm . These results are consistent with the diffusion experiment previously conducted. In addition, the C element content increased at the wear point of the cutting edge, and similar phenomena were also found in other four experimental groups.

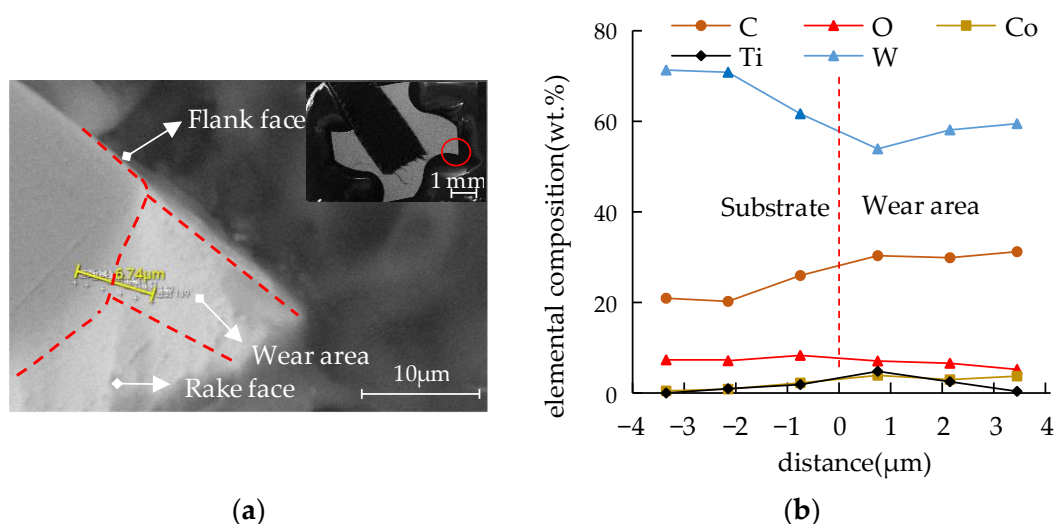


Figure 11. Element diffusion along the tool wear section. (a) SEM image of the cutting edge; (b) Element diffusion curve along the wear area.

The chip obtained during the milling experiment was analyzed by EDS. First, the chip was soaked in alcohol to remove the surface stains. Then, the chip was placed into the SEM to detect the diffusion of the W and Co elements in the Ti6Al4V material. Next, EDS was performed on the chip, as shown in Figure 12. The elemental composition of the chip is shown in Table 9. There was a small amount of the W element in the chip, but no Co. Due

to the low hardness of the Co element, it bonded to the chip surface during the cutting process and peeled off after the cleaning process. The WC grain hardness was higher, and the W element was etched into the chip during the cutting process.

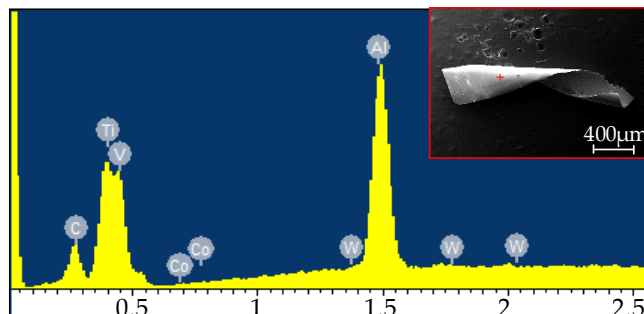


Figure 12. EDS analysis of the chip.

Table 9. Elemental composition of the chip.

Element	Elemental Composition (wt.%)
C	4.87 ± 0.01
Al	5.26 ± 0.01
Ti	86.34 ± 0.01
V	3.45 ± 0.01
W	0.07 ± 0.01

5. Conclusions

The primary friction wear, abrasive wear, adhesion wear, oxidation wear, and diffusion wear of a carbide tool occur when milling titanium alloys. Element diffusion reduces the tool hardness and affects the tool life. It is necessary to study the diffusion between the tool material and Ti6Al4V. In this study, element diffusion between cemented carbide samples with different compositions and Ti6Al4V was investigated. Based on this research, four primary conclusions were drawn:

- (1) The element diffusion experiment showed that element diffusion existed under high-temperature and high-pressure conditions. At the same temperature and pressure, the diffusion amount between the elements was far less than the calculated solubility, which indicates that a chemical reaction took place between the W and Co elements under high-temperature conditions, and that a new phase was produced.
- (2) For the same holding temperature and holding time, the amount and depth of the W and Co element diffused in the Ti6Al4V increased with increases in the element content, while the amount and depth of the Ti elements diffused decreased with increases in the Co element content, because the increase in the Co element content improved the homogeneity of the cemented carbide materials, effectively inhibiting the occurrence of element diffusion. The amount and depth of the W and Co elements diffused in the Ti6Al4V increased with increases in the WC grain size, and the amount of the Ti element diffused increased with increases in the WC grain size. Because the homogeneity of the materials was greater with refinement of the WC grain size, element diffusion was effectively inhibited.
- (3) For a single cemented carbide material, the amount and depth of the W, Co, and Ti elements diffused increased with increases in the temperature and holding time. When the temperature reached 800 °C, the cemented carbide obviously experienced an oxidation reaction.
- (4) An analysis of the cutting edge after a cutting experiment shows that there was Ti in the substrate, which proves the occurrence of the diffusion phenomenon. According

to a chip analysis, no Co was found, and the high hardness of the WC grains led to W etching in the chip.

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