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Effect of Pulse Electromagnetic Coupling Treatment on Thermal Conductivity of WC-8Co Cemented Carbide

Qianwen Zhang[1], Kunlan Huang[1,*], Jie Wang[1], Li Wang[1], Min Yuan[1], Yankang Tian[2], Lin Ouyang[3]

1 School of Mechanical Engineering, Sichuan University, Chengdu, Sichuan 610065, P.R. China
2 Centre for Precision Manufacturing and Micro-Manufacturing, Dept. of DMEM, University of Strathclyde, James Weir Building, 75 Montrose Street, Glasgow G1 1XJ, UK
3 No.5719 factory of PLA, Pengzhou, Sichuan 611937, P.R. China

Abstract: In this study, investigations were conducted focusing on the WC-8Co cemented carbide. A dry turning test of TC4 titanium alloy with WC-8Co cemented carbide tool treated by pulsed electromagnetic coupling treatment (PEMCT) was conducted. Tool wear was observed and analyzed using a scanning electron microscope (SEM) and energy dispersive X-ray spectrometer (EDS). The thermal conductivity of WC-8Co cemented carbide before and after the PEMCT was measured using Hotdisk thermal conductivity analyzer. The finite element software, DEFORM, was used to simulate the cutting process, and the stable cutting temperature range was obtained. The high-temperature oxidation test was conducted in a muffle furnace to study the effect of the PEMCT on the oxidation resistance of WC-8Co cemented carbide. This study obtained the effect of the PEMCT on the thermal conductivity of tungsten cobalt cemented carbide. The results show that the PEMCT can reduce the adhesive, diffusion, and oxidation wear of the tools, thus, improving the wear resistance and service life of the tools. The PEMCT improves the thermal conductivity and diffusivity of WC-8Co cemented carbide. Moreover, the oxidation resistance of WC-8Co cemented carbide in high-temperature conditions can be improved.

Keywords: Pulse electromagnetic coupling; Cemented carbide; Thermal conductivity; Oxidation resistance

Corresponding Author Details:

Name: Kunlan Huang, Ph.D

Email address: huangkunlan@scu.edu.cn

1. Introduction

Tungsten cobalt cemented carbide is composed of hard phase WC and binder phase Co, which has good strength, toughness and red hardness [1,2]. It has been used in the fields of metal cutting, metal forming and wear-resistant structural components [3,4]. The cutting load is heavy and the cutting temperature is high when using cemented carbide tools to cut superalloy materials because of the large plastic deformation resistance and poor thermal conductivity of superalloy. This results in accelerated tool wear, which reduces the surface quality of workpieces and tool life [5-7]. Therefore, it is important to improve the thermal conductivity and oxidation resistance of cemented carbide materials.

The thermal conductivity of tungsten cobalt cemented carbide is controlled by changing the grain size and cobalt content of tungsten carbide. Fine WC grain and high Co content contribute lower thermal conductivity [3,8-10]. It is found that that cryogenic treatment can increase the thermal conductivity and diffusivity of WC-Ni cemented carbide [11]. After adding graphene and carbon nanotubes to WC-Co powder for mixed sintering, the thermal conductivity and bending strength improved [12].

Several studies have been conducted on the performance of cemented carbide in a high-temperature environment: L. Y. Chen et al. [13,14] studied the selective oxidation behavior of WC-Co cemented carbide and found that the oxidation of Co phase preceded that of WC phase; L. Del Carnpo et al. [15] studied the isothermal oxidation behavior of WC-based cemented carbide between 450 °C and 800 °C and found the effect of the composite oxide $CoWO_4$ on oxidation kinetics. A large number of studies have found that the oxidation behavior of WC-Co cemented carbide increases with the decrease of Co content and the increase of oxygen concentration [16-19]. Z. H. Jiang [20] used the WC-8Co tool to dry cut TC4 titanium alloy and found that the tool suffered from adhesive and oxidation wear.

The strengthening treatment technologies for cemented carbide include heat-treatment and ultra-fine cemented carbides [21,22], which are based on the phase transformation and connection distribution improvement between binder phase and hard phase, or technologies, such as tool-coating and cryogenic treatment [23-26], which are based on adding or generating hard phase, that will inhibit the wear of the alloy, on the surface of the material. In this study, pulse electromagnetic coupling treatment (PEMCT) technology is proposed to strengthen the WC-8Co cemented carbide and improve its thermal conductivity and oxidation resistance.

Researchers have studied the influence of the coupled electric and magnetic field treatment on materials. Electromagnetic treatment reduces the friction coefficient of cemented carbide tools, improving wear resistance and prolonging service life [27,28]. Electromagnetic treatment technology reduces the flank wear of cemented carbide-milling cutter. The dislocation strengthening is the reason for improved mechanical properties [29,30]. Electromagnetic treatment reduces the entanglement and plug of dislocation lines in titanium alloy [31]. In the PEMCT, the magnetic field and electric field provide the driving force for dislocation motion [32-35], rearrange the distribution of dislocations, reduce the dislocation cellular structure, and make dislocations entangled at the grain boundaries evenly distributed in the crystal [29,36].

Presently, the research on the PEMCT of cemented carbide materials focuses on the tool's cutting performance and tribological behavior with little attention paid to the thermal conductivity and oxidation behavior of cemented carbide materials after the PEMCT. Therefore, this study investigates the effect of the PEMCT on the thermal conductivity and oxidation behavior of cemented carbide. The dry turning experiment of TC4 titanium alloy with WC-8Co cemented carbide tool treated by PEMCT was conducted, and the cutting temperature and tool wear were obtained. Thermal conductivity, thermal diffusivity, and electrical conductivity were measured to evaluate the effect of PEMCT on heat conduction of cemented carbide materials. The high-temperature oxidation test was conducted to evaluate the effect of PEMCT on the oxidation resistance of cemented carbide materials.

2. Experiment

2.1 Pulse electromagnetic coupling processing

The PEMCT is used to process WC-8Co cemented carbide specimens and tools of the same production batch, which are provided by Zhuzhou Cemented Carbide Group Co., Ltd. The mean tungsten carbide grain size in as-sintered specimens was found to be around 0.671 μm. The self-development PEMCT apparatus was used to treat the samples. The schematic of the PEMCT apparatus is shown in Fig. 1(time of the PEMCT). The copper electrodes at both ends clamp the sample and apply pulse current, the excitation coil provides an external magnetic field, and the power supplies of the electrodes and the excitation coil work synchronously through PLC, finally achieving the effect of PEMCT. Table 1 shows the parameters of the PEMCT in this experiment.

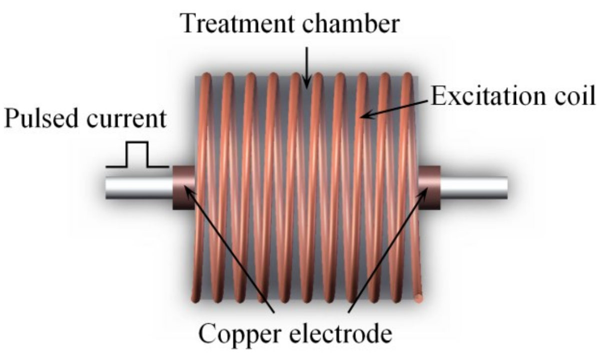

Fig. 1 Schematic of pulse electromagnetic coupling-processing device

Table 1. Processing parameters of pulse electromagnetic coupling treatment

Treatment	Magnetic field parameters			Pulse Current Parameters			Processing time (s)
	Intensity (T)	Frequency (Hz)	Pulse Number	Voltage (V)	Frequency (Hz)	Pulse Number	
UT	—	—	—	—	—	—	—
PEMCT	1.5	1.0	20	1.2	50	250	250

2.2 Cutting experiment

The dry excircle turning test on NC lathe (G-CNC6135) was used to study the effect of the PEMCT on the wear performance of cemented carbide. The workpiece material is TC4 titanium alloy, which is used in aerospace. The diameter and length of the workpiece are 60 mm and 300 mm, respectively. Due to the low thermal conductivity of titanium alloy, high cutting temperature and serious oxidation wear of the cutting tool were observed in the machining process [20,37]. The reason for selecting TC4 is to study the effect of PEMCT on the thermal conductivity and oxidation resistance of cemented carbide. The physical properties of TC4 titanium alloy are shown in Table 2. The tool model of WC-8Co cemented carbide is 31303C and its geometric parameters and physical properties are shown in Table 3. and Table 4., respectively. In this experiment, five trials were conducted under the same cutting conditions, including three untreated control groups (UT-1, UT-2, UT-3) and two experimental groups with the same PEMCT parameters (PEMCT-1, PEMCT-2). Multiple control groups and experimental groups were used to ensure the accuracy of the test data and reduce the random error. The turning parameters are shown in Table 5. After preliminary experiments, it is found that the cutting distance is about 1800 mm when the flank wear value (VB) reaches 0.3 mm. Therefore, the tool flank wear is observed and recorded using an image measuring instrument (VMS3020) for every 450 mm, and its wear morphology captured. The insulated thermocouple (5TC-TT-K-30-36) and data acquisition module (OM-DAQ-USB-2401) of OMEGA Engineering Inc. are used to measure and collect the cutting temperature of the tool flank. The schematic of cutting experiment setup is shown in Fig. 2. A micro hole with a diameter of 1 mm is machined at a vertical distance of 2 mm from the cutting edge, as shown in Fig. 3. The thermocouple is embedded in the hole, and the gap between the thermocouple end and the hole is filled with thermal conductive silicone grease.

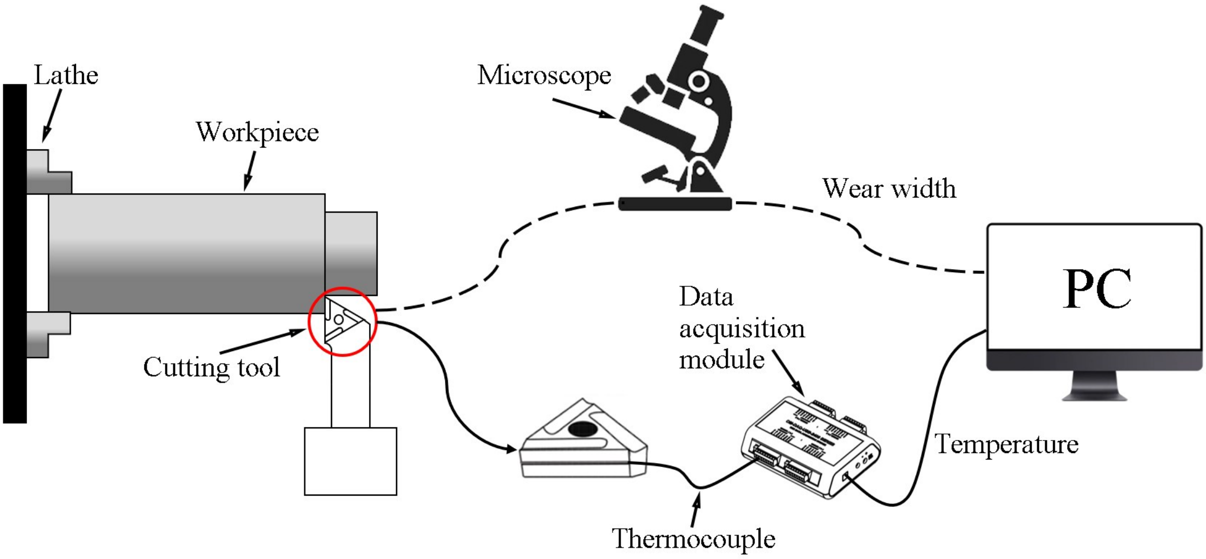

Fig. 2 Schematic of cutting experiment setup

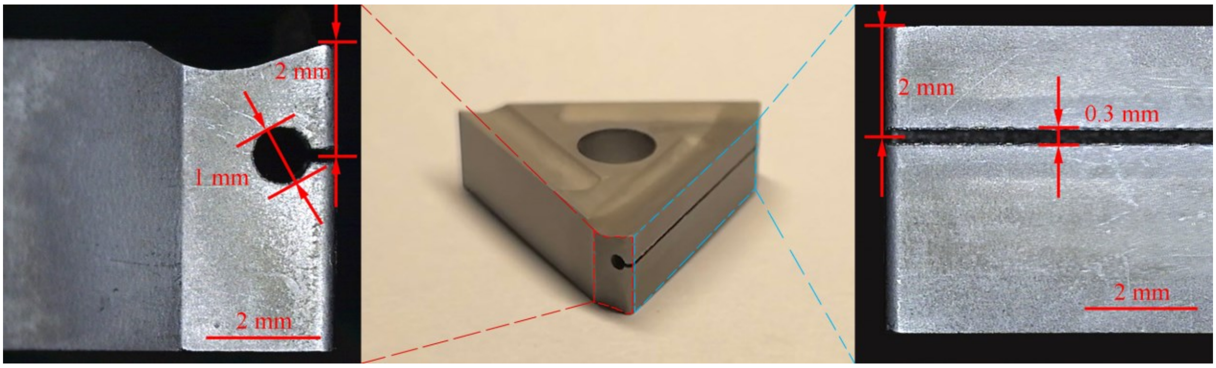

Fig. 3 Illustration of thermocouple installation in the WC-8Co cutting tool

Table 2. Physical properties of TC4 titanium alloy

Elastic modulus (GPa)	109
Yield strength (MPa)	817
Poisson's ratio (v)	0.41
Thermal conductivity (W/m·K)	8
Specific heat (J/kg)	1002
Melting point (°C)	1589
Density (kg/m^3)	4384
Hardness (HV)	363

Table 3. geometric parameters of tool model

Rake angle	Rear angle	Auxiliary rear angle	Inclination angle	Chip discharge groove width	Rounded cutting edge radius
2°	6°	6°	0°	0.5 mm	0.1 mm

Table 4. Physical properties of WC-8Co cemented carbide

Hardness (HV)	1496
Bending strength (MPa)	1500
Compressive strength (MPa)	4470
Elastic modulus (GPa)	600~610
Impact toughness (J/cm^2)	2.5
Density (kg/m^3)	14600
Thermal conductivity (W/m·K)	12

Table 5. Turning parameters

Cutting depth (mm)	0.25
Feed speed (mm/min)	60
Cutting speed (mm/min)	80
Cutting length (mm)	150

2.3 High-temperature oxidation experiment

The oxidation experiment was performed in a muffle furnace. The size of WC-8Co cemented carbide specimens is 6 × 6 × 20 mm, and the electromagnetic treatment parameters are UT and PEMCT. After polishing, cleaning, and drying, the specimens were weighed three times on the electronic balance, and the average values were recorded. The muffle furnace was preheated to the required temperatures of 800 °C, 850 °C, 900 °C, 950 °C, and 1000 °C, respectively. The UT and PEMCT specimens (10 specimens, divided into 5 groups) were placed in a crucible and kept in the muffle furnace for 50 min. The space in the muffle furnace is a vacuum. The crucible was removed from the muffle furnace and the specimens were cooled to room temperature in air. The weights of the cooled specimens were measured. The surface morphology and elemental analysis of the oxidation layer were observed by SEM (Thermo Scientific Apreo S–USA) and EDS (AZtec X-Max 80–Oxford Instruments), respectively.

3. Results and discussion

3.1 Effect of PEMCT on wear behavior of cemented carbide

According to ISO 08688–1 standard, the tool is considered blunt when the flank wear (VB) reaches 0.3 mm. Fig. 4 shows the wear curve of the flank. Fig. 5 is a comparison of the VB between the untreated tool and the PEMCT tool.

Fig. 4 shows that the wear curve of the flank have wear stages: initial, normal, and acutely worn. At different cutting lengths, the VB of the PEMCT tools is much lower than that of the UT tools. When the cutting distance reaches 1800 mm, the VB of the three untreated groups meets the failure limit of 0.3 mm. The average value of the VB of the two PEMCT groups is 0.164 mm, and the flank wear is reduced by 45%.

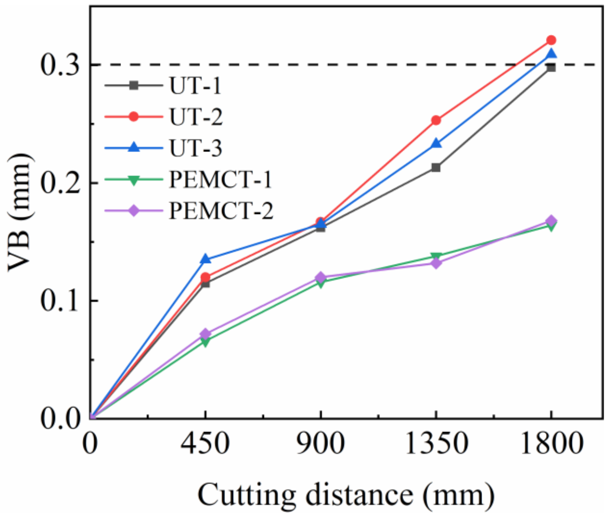

Fig. 4 Curves of flank wear

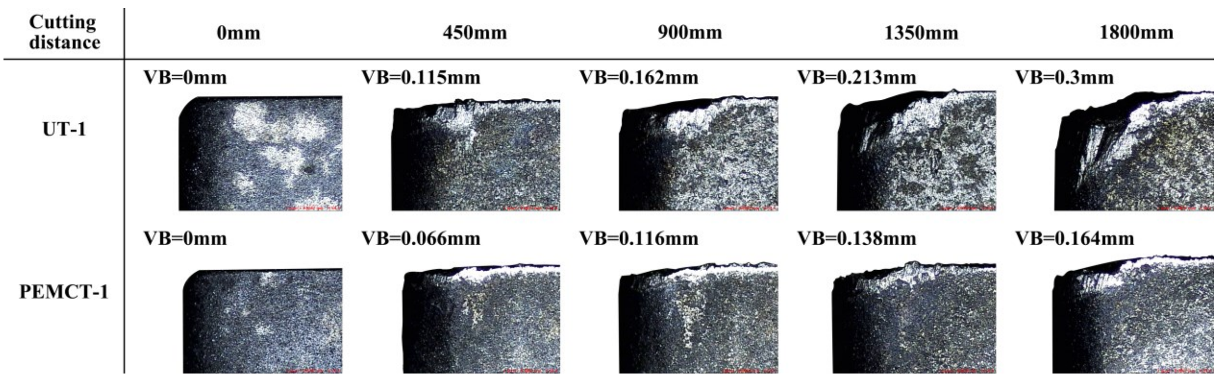

Fig. 5 VB wear of UT-1 and PEMCT-1 per 450 mm

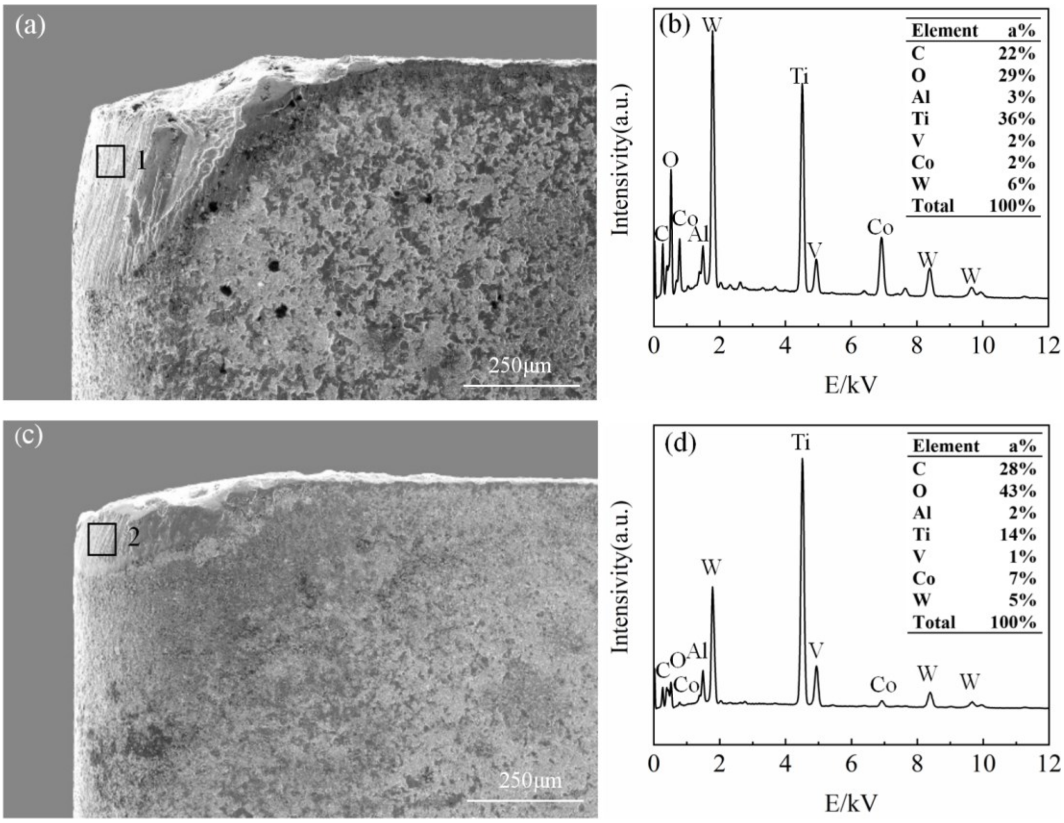

Fig. 6 SEM morphology and EDS energy spectrum of tool wear area (cutting distance of 1800 mm). (a) UT-1; (b) point 1; (c) PEMCT-1; (d) point 2

Fig. 6 (a) and (b) show the SEM morphology of the wear area of the tool flank. The main wear forms of cemented carbide tools when turning titanium alloy exhibit adhesive, diffusion, and oxidation wear. Cutting temperature is the main factor that affects tool wear. When cutting titanium alloy, the maximum cutting temperature of cemented carbide tools is between 800 °C–1000 °C [38,39]. Difficulty in allowing air to enter the cutting area leads to the reaction of the air reacts with WC and Co in WC-8Co cemented carbide at the cutting boundary position of the tool flank where the temperature is high, forming an oxide scale with low hardness and strength. During the cutting process, the oxide scale generated on the tool flank rubs against the oxide layer, cooling the hard layer, and hard spots on the workpiece surface, which cause boundary oxidation wear on the flank. Comparing the UT-1 tool with the PEMCT-1 tool, it can be seen that the untreated tool is seriously worn, the adhesive wear of the flank is obvious, and the oxidation wear groove is formed at the cutting boundary position. After the PEMCT, the wear volume of the flank was reduced, the degree of adhesive wear and oxidation wear weakened, and the boundary of the wear area becomes smoother. The experimental results show that the PEMCT can effectively improve the wear resistance of cemented carbide tools.

When dry turning TC4 titanium alloy with WC-8Co cemented carbide tool at high temperature and pressure, the binder phase Co and the W and C decomposed from the hard phase WC diffuse to the workpiece material, diluting the matrix elements and the reduction of the wear resistance of the tool surface. In addition, due to the loss of the binder phase Co, more micropores appear in the cemented carbide, decreasing the bond strength on the surface, which sheds the WC particles and further accelerates the wear of the tool flank.

To clarify the effect of the PEMCT on wear behavior, EDS is conducted at points 1 and 2 in the areas with smooth wear on the flank of the UT-1 and PEMCT-1 tools shown in Fig. 6 (a), (b) respectively. The analysis results are shown in Fig. 6 (c), (d). Fig. 7 shows the EDS elemental surface scanning of the tool wear area. The EDS elemental surface scanning shows that the matrix elements of wear area are replaced by Ti. It can be found from the energy spectrum (Fig. 6 (b)) that Ti, V, and Al are the main elements in the sampling point of the UT-1 tool, accounting for 41% of the total elements. This indicates that the wear at the flank is diffusion wear, while the sampling point of the PEMCT-1 tool is mainly composed of W, C, and Co elements, and the contents of Ti, V, and Al are far lower than those in the UT-1 tool, which accounts for only 17% of the total elements, with a decrease rate of 59%. The results show that the PEMCT reduced the element diffusion between the workpiece and tool. Cutting temperature is a direct factor affecting tool diffusion wear. The higher the cutting temperature, the stronger the chemical affinity between the tool and workpiece. The element diffusion is more dramatic at the same time. Finally, leading to the aggravation of tool wear. The O content of the PEMCT-1 tool is higher than that of the UT-1 tool, i.e. 43% and 29%, respectively. This phenomenon does not show that the PEMCT will aggravate the tool oxidation wear. First, the EDS is conducted at the contact area between the flank and the machined surface, and oxygen is not easily accessible due to the high temperature and pressure. Adhesive and diffusion wear occurs in this area, and oxidation wear accounts for a small proportion. Second, as the diffusion wear decreases, elements, such as Ti, Al, and V decrease. Therefore, the proportion of O and other residual elements increases. Finally, due to the higher oxygen content in this area, it shows that the oxide in this area is barely carried away by the adhesive wear, which proves that the adhesive wear has been improved.

Therefore, it is proved that the PEMCT can improve the thermal conduction of WC-8Co cemented carbide and reduce the cutting temperature during the cutting process, thus achieving the effect of improving the tool wear behavior.

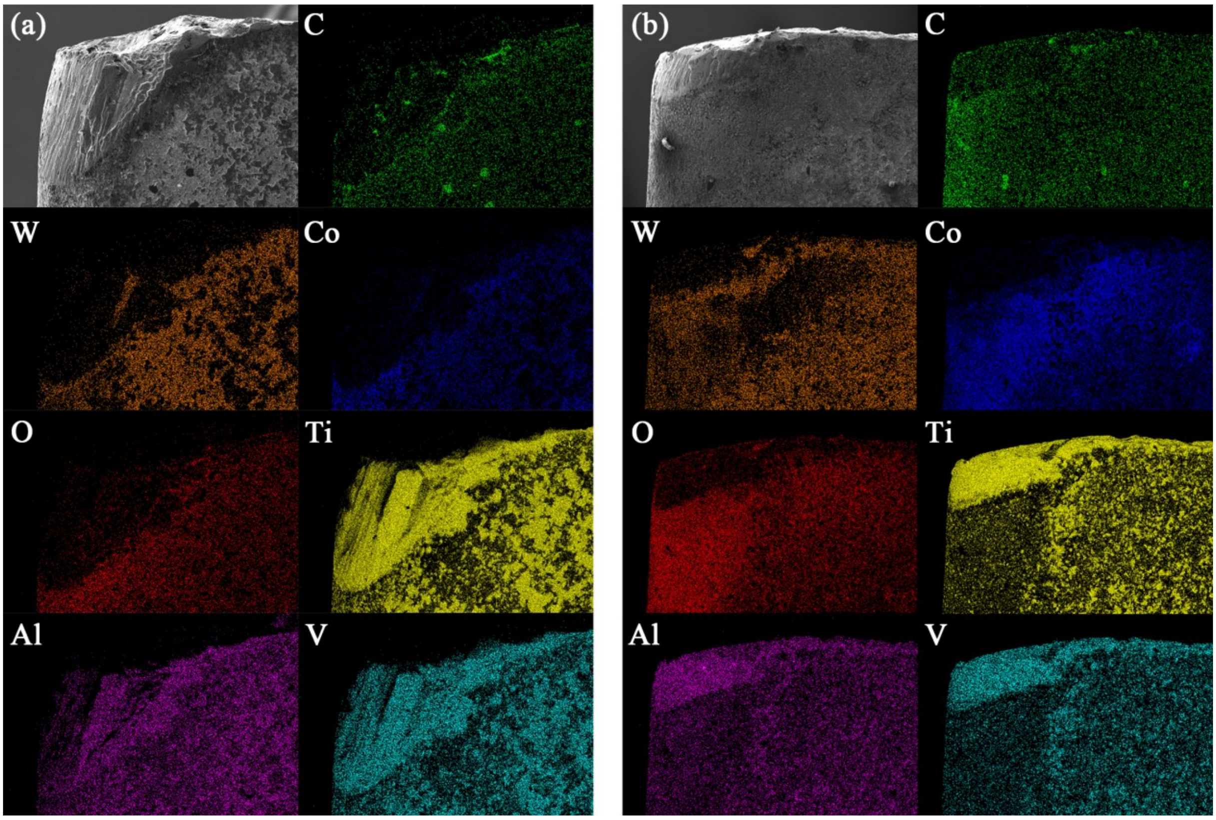

Fig. 7 Energy spectrometer element surface scanning of tool wear area. (a) UT-1; (B) PEMCT-1

3.2 Effect of the PEMCT on thermal conduction of cemented carbide

To verify the above inference, thermal conductivity at room temperature of WC-8Co cemented carbide specimens with the size of 6 × 6 × 10 mm was measured using Hotdisk Thermal Constant Analyzer (TPS2500S) according to ISO22007-2.2008 standard and the experimental results are shown in Table 6.

WC-8Co cemented carbide is composed of phases with different heat transfer mechanisms. Hard phase WC transfers heat through lattice vibration (phonon conduction), whereas the binder phase Co transfers heat through free electron movement (electron conduction). The thermal conductivity of hard phase WC and binder phase Co can be described by the thermal conductivity formula for an ideal gas:

$$\lambda = \frac{1}{3} C_V \bar{\upsilon} l \qquad (1)$$

where C_V is the phonons (electrons) heat capacity per unit volume, $\bar{\upsilon}$ is the average velocity of phonons (electrons), l is the mean-free path of phonons (electrons).

The relationship between thermal conductivity λ and electrical conductivity σ described by Wiedemann-Franz law:

$$\frac{\sigma}{\lambda} = LT \qquad (2)$$

where L is the Lorentz constant, the theoretical value is 2.44×10^{-8} $W\Omega K^{-2}$, and T is experimental temperature. WC-8Co cemented carbide contain simple composition, and its heat and electric conduction are similar to that of metal [8,40]. Therefore, the digital conductivity meter (Sigma 2008B) is used to test the electric conductivity of the specimens before and after the PEMCT, three times at room temperature. Table 7 shows the average of the measurement results.

From Table 6, we can find that the PEMCT can improve the thermal conduction capability of WC-8Co cemented carbide. The thermal conductivity and diffusivity of specimens increased by 18% after the PEMCT. With the increase in the thermal conductivity of the tool, the heat accumulated in the contact area between the rake face, chip, and workpiece conducted through the tool, decreasing the maximum cutting temperature; thus, the diffusion and oxidation wear caused by high temperature are reduced. This process helps in prolonging the service life of the tool.

Table 7 shows that the electrical conductivity of WC-8Co cemented carbide increased by 6% after the PEMCT, which proves that the PEMCT can improve the thermal conductivity. The ratio of electrical conductivity to the thermal conductivity of cemented carbide before and after PEMCT is not a constant, which indicates that phonons have a greater influence on thermal conductivity than electrons in WC-8Co cemented carbide heat transfer mechanism.

Table 6. Effect of PEMCT on thermal conduction capability of WC-8Co cemented carbide

Treatment	**Thermal conductivity (W/mK)**	**Thermal diffusivity (mm^2/s)**
UT-1	33.32	11.59
UT-2	33.56	11.67
UT-average	33.44	11.63
PEMCT-1	39.16	13.62
PEMCT-2	39.84	13.86
PEMCT-average	39.50	13.74

Table 7. Effect of PEMCT on electrical conductivity of WC-8Co cemented carbide

Treatment	**Electrical conductivity (mS/m)**
UT	2.2550
PEMCT	2.3834

Defects and grain boundaries in cemented carbide crystal structure act as scattering centers of electrons and phonons [41]. Grain boundaries promote the scattering of electrons (phonons) and block heat flow. The existence of defects reduces the mean-free path of phonons (electrons), thus reducing the thermal conductivity of cemented carbide [42]. The concentration of defects at grain boundaries is higher than that in grains (WC phase and Co phase) [43].

The PEMCT facilitated the dislocation movement through the driving force provided by the magnetic and electric field, homogenized the distribution of dislocations inside the crystals. Therefore, the scattering of electrons and phonons decreases, increasing their mean-free path, which leads to the increase in thermal conductivity. Co is a paramagnetic element. The separation of impurities and vacancies in the magnetic domain atomic layers is reduced by a magnetic field [30], while the scattering of electrons is reduced. However, Co atoms are arranged in a linear chain to form an efficient channel for heat transfer [44]. The thermal conductivity increases due to a combined effect described above. However, the PEMCT improves the solubility of W and C atoms in the Co phase, forming a solid solution with Co as the solvent and increasing the scattering of electrons in the Co phase [9,10,43]. This scattering of electrons reduces thermal conductivity. The final thermal conductivity shows an increasing trend because defects have a greater influence on the thermal conductivity than the solid solution.

The finite element software Deform is used to simulate the cutting process of TC4 titanium alloy using the WC-8Co cemented carbide tool. The temperature field distribution of the cutting tool is obtained and the simulation results are shown in Fig. 8. The highest temperature area is in the contact area between the rake face and chip. The range of the stable cutting temperature is 800 °C–1000 °C.

Fig. 9 shows the cutting temperature of the flank measured using a thermocouple. It can be found from the temperature curve that the cutting temperature of the PEMCT tools decreased with an average decrease in amplitude by 19%. The heat conductivity of WC-8Co cemented carbide improved after the PEMCT, changing cutting heat partition. The cutting heat is transferred to the tool body from the cutting edge. Therefore, the average temperature inside the PEMCT-1 tool is higher than that inside the UT-1 tool. However, the experimental results show that the cutting temperature decreases after the PEMCT. The reason for the decrease is because the temperature measurement position in this experiment is near to the tool's tip, where the cutting heat is transferred into the tool body, rather than the whole tool body. As the thermal conductivity of the tool increases, after PEMCT, the speed of heat transfer from the tool's tip to the whole tool body increases, and the temperature gradient of the whole tool body decreases. Therefore, the temperature of the PEMCT-1 is lower than that of the UT-1.

The influence of thermal conductivity on cutting temperature is studied by cutting simulation. The thermal conductivity measured before and after the PEMCT (Table 6) is assigned to the tool material, respectively. Fig. 10 shows the cutting temperature comparison when the number of simulation steps is 8000. The cutting temperature of the tool's tip obtained from simulation is shown in Fig. 11. The simulation results show that when the thermal conductivity of the tool increases, the cutting temperature of the tool's tip decreases by 20%, which is consistent with the experimental results.

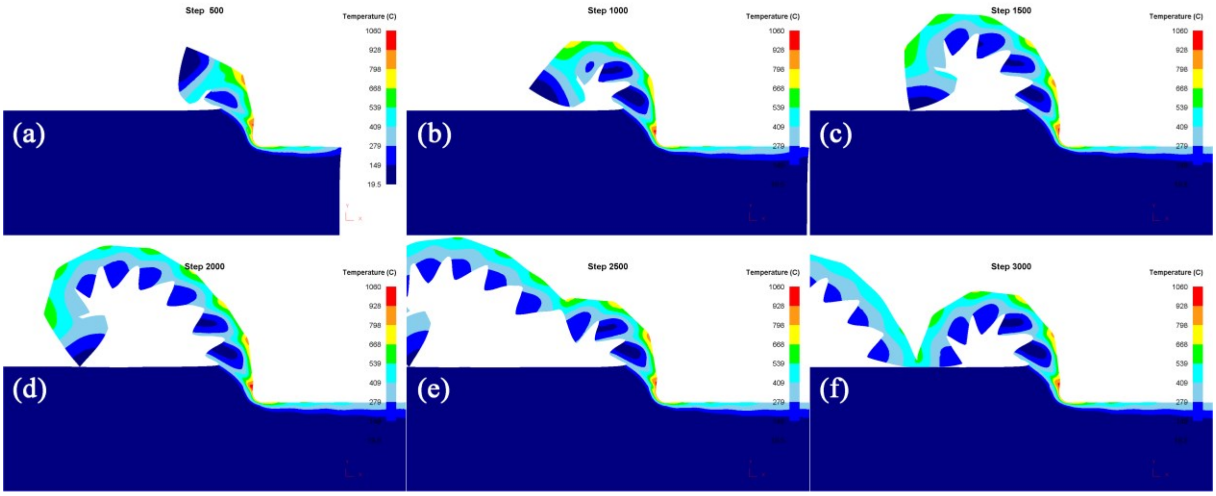

Fig. 8 Simulation of cutting temperature. (a) step 500; (b) step 1000; (c) step 1500; (d) step 2000; (e) step 2500; (f) step 3000

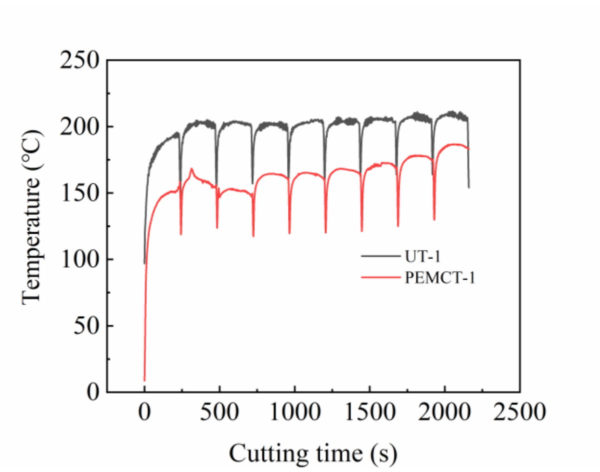

Fig. 9 Cutting temperature of flank

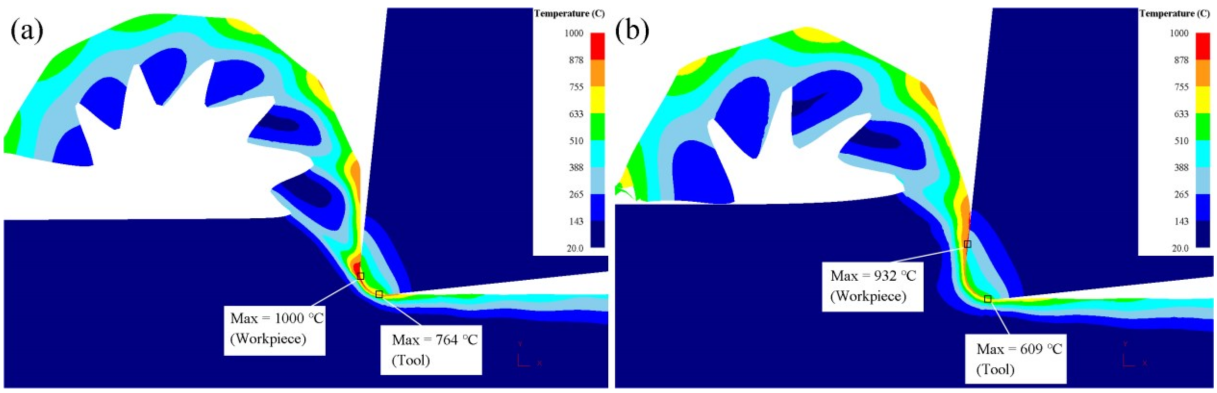

Fig. 10 Simulation of cutting temperature at step 8000. (a) UT-1; (b) PEMCT-1

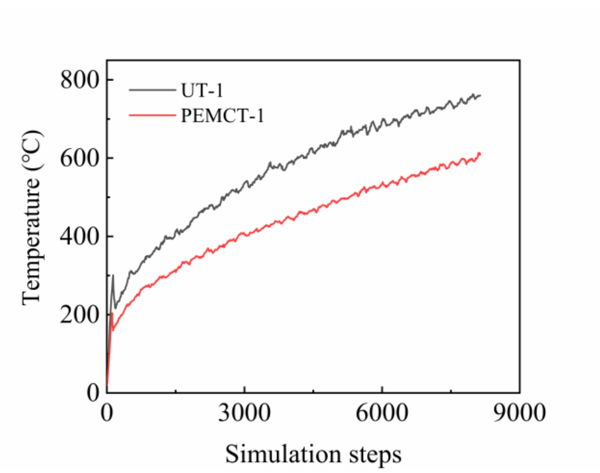

Fig. 11 Simulation of cutting temperature at tool's tip

3.3 Effect of PEMCT on the oxidation resistance of cemented carbide

The oxidation resistance of tungsten cobalt cemented carbide tools at high temperatures determines their service life. During the oxidation process, the oxide scale which flakes will form, reducing the wear resistance of cemented carbide tools. Therefore, it is important to study the oxidation resistance of cemented carbide after the PEMCT.

Fig. 12 shows the morphology of WC-8Co cemented carbide specimens oxidized at different temperatures under different treatment processes. A large amount of blue oxide is generated on the surface of the specimens, and the thickness of the oxide layer increases with an increase in temperature, and the volume of the specimens expands sharply when the temperature rises to 900 °C.

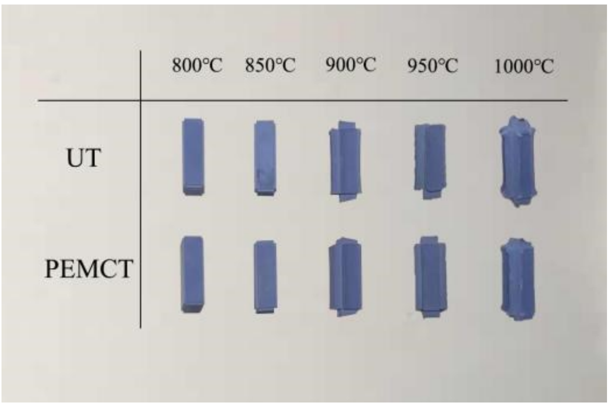

Fig. 12 Surface conditions after oxidation at different temperatures

The oxidation degree of WC-8Co cemented carbide varies with temperatures. To study the effect of the PEMCT on the oxidation resistance of WC-8Co cemented carbide, the oxidation mass gain ΔW is introduced here to quantitatively study the oxidation resistance of the specimens:

$$\Delta W = \frac{W_2 - W_1}{S} \tag{3}$$

where W_1 and W_2 are the masses of the specimens before and after oxidation, respectively. S is the total surface area of the specimens (cm^2). The oxidation mass gain of the UT and PEMCT specimens at different temperatures are calculated and displayed in the form of curves, i.e. the oxidation mass gain curves of WC-8Co cemented carbide specimens (Fig. 13).

Fig. 13 shows obvious oxidation of the specimens at 800 °C, and the oxidation rate starts to accelerate after 850 °C. With the increase of temperature, the gap between oxide particles on the cemented carbide surface increases, and air, which promotes oxidation behavior, continuously enters the cemented carbide matrix. In contrast, the oxidation mass gain decreases between 900 °C–950 °C. This decrement is because WO_3 produced by WC oxidation will sublimate when the temperature exceeds 900 °C [45,46], and the oxidation rate of WC is lower than the sublimation rate of WO_3, decreasing oxidation mass gain curves. The sublimation of WO_3 increases the gap between oxide particles, accompanied by cracks and other defects caused by the escape of CO_2. Therefore, more WC-8Co cemented carbide matrix exposed to air, resulting in intense oxidation of specimens. At this stage, WC is oxidized to WO_3, and the rapid sublimation of WO_3 exposes the WC matrix, which is a process of mutual influence and promotion. When the temperature reaches 950 °C, the oxidation mass gain of specimens continues to increase. This increase is because the composite oxide $CoWO_4$ forms a dense oxide layer on the surface of the specimens to prevent the sublimation of WO_3 and the infiltration of oxygen into the cemented carbide matrix.

The oxidation resistance of the PEMCT is better than that of the UT, and the effect is significant with the temperature increase. After the PEMCT, the oxidation mass gain of the specimens can be reduced by 21.14mg/cm^2 (at most). Under the action of the electromagnetic field, the internal defects and intercrystalline pores of cemented carbide reduced. Thus, the defects caused by the formation of the oxide layer are reduced accordingly, and the oxide layer becomes uniform and dense. This prevents the penetration of oxygen into the specimen's matrix, thus, improving the oxidation resistance of specimens. In addition, the promotion of the solid solution of W and C atoms in the Co phase mentioned above improves the solid solution reaction in the Co phase:

$$Co+W+C+3O_2=CoWO_4+CO_2 \qquad (4)$$

promote the formation of the $CoWO_4$ oxide layer.

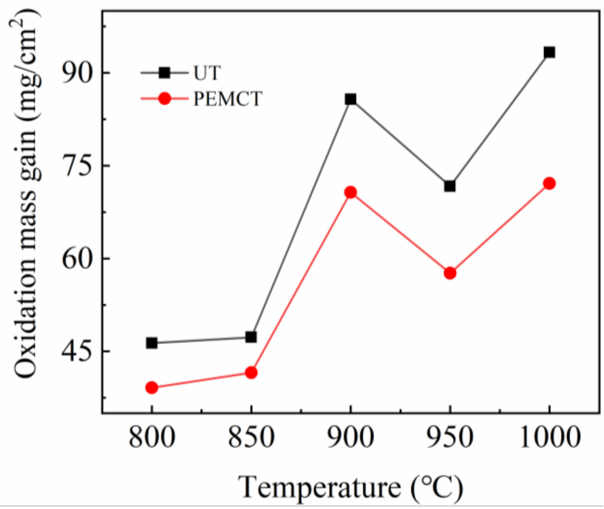

Fig. 13 Oxidation mass gain curve

Fig. 14 shows SEM micrograph and EDS energy spectrum of oxide surface of specimens. Before the SEM and EDS observation, the samples were sputtered Au. Therefore, the Au is ignored in the following element composition statistics. SEM micrograph shows that the oxide particles on the surface of specimens treated at 800 °C and 850 °C are fine and densely arranged, while the oxide particles grow rapidly and cracks appear on the oxidation surface of specimen treated at 900 °C. The specimen treated at 950 °C shows that, in addition to the coarse oxide particles, the newly exposed WC is oxidized to fine particles. At 1000 °C, the surface of the specimens is covered with a dense layer of coarse and uniform composite oxide $CoWO_4$. The SEM morphology of the oxide surface is consistent with the analysis of the oxidation mass gain curves mentioned above.

According to data from the EDS, the difference in element contents between the UT and PEMCT is obvious between 800 °C–900 °C. While there is a slight difference at 950 °C and 1000 °C. Comparing the EDS energy spectrum for specimens heated to 900 °C (Fig. 14 c-1, c-4), found that the content of the O atom on the surface of the PEMCT specimen is 18%, which is 9% higher than that of the UT specimen. While the C atom content of the UT specimen is 12% higher than that of the PEMCT specimen. It is proved that the specimens gotten after the PEMCT generate a more uniform and compact $CoWO_4$ oxide film that prevents WC from oxidation. Moreover, the content of the Co atom percentage of the PEMCT specimen is 2% higher than that of the UT specimen. It shows that the PEMCT can prevent the dilution of the Co element on the surface of the WC-8Co cemented carbide during the oxidation process. The EDS energy spectrums of specimens oxidized at 950 °C and 1000 °C show little difference because the surface is oxidized completely.

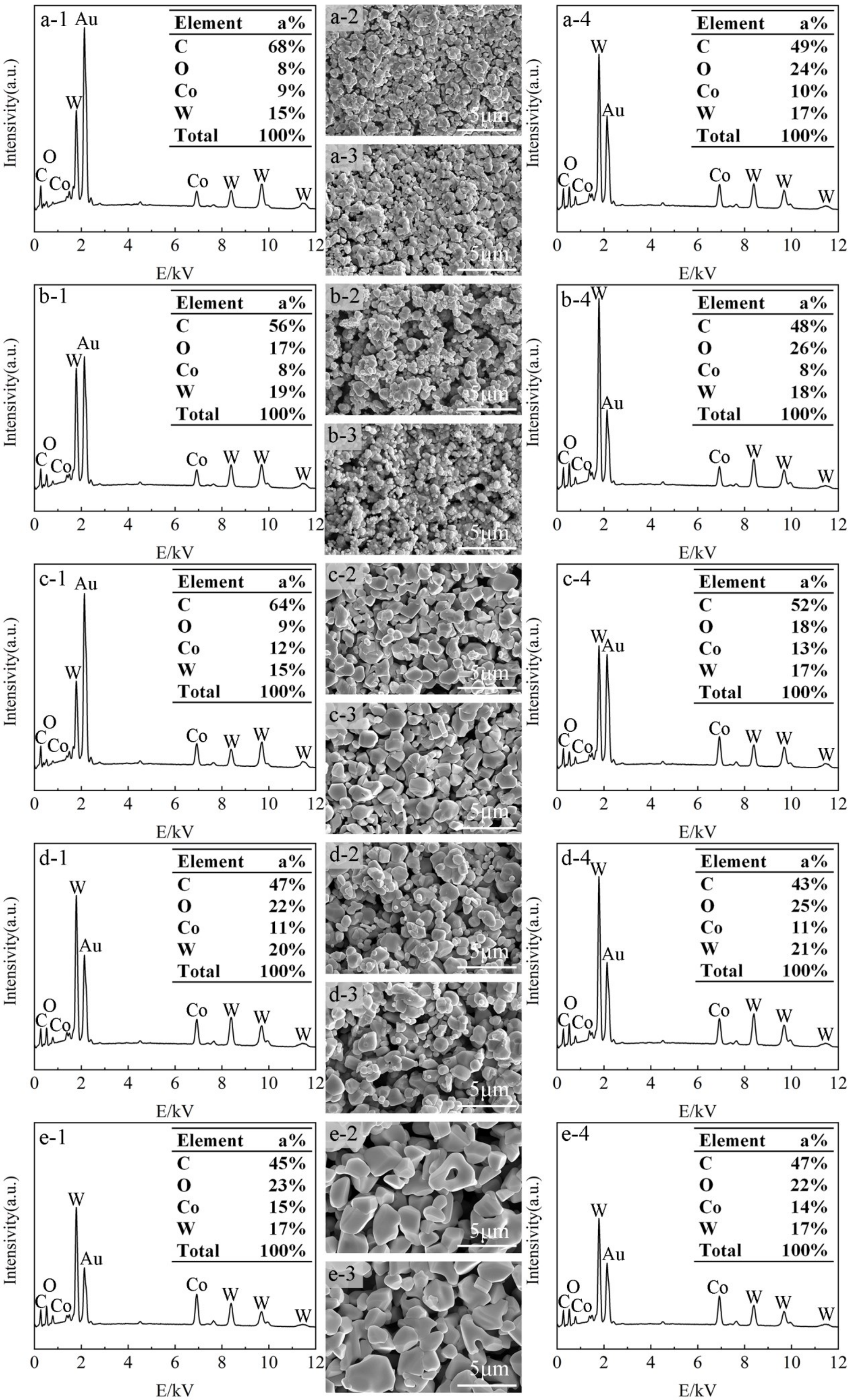
a-1
Element a%
C 68%
O 8%
Co 9%
W 15%
Total 100%
a-2
a-3
a-4
Element a%
C 49%
O 24%
Co 10%
W 17%
Total 100%
b-1
Element a%
C 56%
O 17%
Co 8%
W 19%
Total 100%
b-2
b-3
b-4
Element a%
C 48%
O 26%
Co 8%
W 18%
Total 100%
c-1
Element a%
C 64%
O 9%
Co 12%
W 15%
Total 100%
c-2
c-3
c-4
Element a%
C 52%
O 18%
Co 13%
W 17%
Total 100%
d-1
Element a%
C 47%
O 22%
Co 11%
W 20%
Total 100%
d-2
d-3
d-4
Element a%
C 43%
O 25%
Co 11%
W 21%
Total 100%
e-1
Element a%
C 45%
O 23%
Co 15%
W 17%
Total 100%
e-2
e-3
e-4
Element a%
C 47%
O 22%
Co 14%
W 17%
Total 100%
Intensity(a.u.)
E/kV
Au
W
C
O
Co
5μm

Fig. 14 SEM micrograph and EDS energy spectrum of the UT and PEMCT samples oxidized at different temperatures. (a-1, a-2) UT, 800 °C; (a-3, a-4) PEMCT, 800 °C; (b-1, b-2) UT, 850 °C; (b-3, b-4) PEMCT, 850 °C; (c-1, c-2) UT, 900 °C; (c-3, c-4) PEMCT, 900 °C; (d-1, d-2) UT, 950 °C; (d-3, d-4) PEMCT, 950 °C; (e-1, e-2) UT, 1000 °C; (e-3, e-4) PEMCT, 1000 °C

4. Conclusions

In this study, the PEMCT of WC-8Co cemented carbide was conducted, and the wear properties, thermal conduction capability, and oxidation resistance of cemented carbide were studied. The results show that:

1) The PEMCT can reduce the adhesive, diffusion, and oxidation wear in WC-8Co cemented carbide cutting tool and improve its cutting performance and service life.

2) The PEMCT can improve the thermal conduction capability of WC-8Co cemented carbide. After the PEMCT, the thermal conductivity, thermal diffusivity, and electrical conductivity increased by 18%, 18%, and 6%, respectively. Cemented carbide tools with high thermal conductivity can reduce the maximum cutting temperature.

3) The PEMCT can improve the oxidation resistance of WC-8Co cemented carbide. The oxidation mass gain of the specimen after the PEMCT can be reduced by 21.14 mg/cm^2 (at most). The reduction of internal defects of WC-8Co cemented carbide and the promotion of solid solution of Co phase are mechanisms to enhance the oxidation resistance.

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