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ARTICLE

Cutting Mechanism of WC-8Co Cemented Carbide for Dry Turning of Ti6Al4V Before and After Pulsed Electromagnetic Coupling Processing

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Abstract: Pulsed electromagnetic coupling treatment equipment was used to strengthen WC-8Co cemented carbide. The mechanical and frictional properties of WC-8Co were studied, and the strengthening mechanism was revealed by analyzing the cutting performance. The cutting behavior of Ti6Al4V in dry turning was analyzed by collecting the cutting force, temperature, and wear signals of the flank surface on the tool in the turning test. Finally, scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) were used to observe and analyze the WC-8Co cemented carbide. The aim was to reveal the cutting mechanism of WC-8Co cemented carbide for dry turning of Ti6Al4V before and after pulsed electromagnetic coupling processing. The results show that pulsed electromagnetic coupling processing can improve the durability of tools while reducing the temperature of the cutting and the oxidation wear of the flank surface of the tools.

Key words: pulsed electromagnetic coupling; WC-8Co cemented carbide; Ti6Al4V; cutting mechanism

Ti6Al4V is an important titanium alloy used in the aerospace, medical, and chemical industries. It is a typical hard-to-machine material that can create a high cutting temperature and induce severe tool wear in the cutting process because of its poor thermal conductivity, high chemical activity, and small elastic module[1-3]. Meanwhile, tool wear is a critical factor that hinders the cutting speed and the use of titanium alloy, leading to the high manufacturing cost for parts of titanium alloy. Therefore, it is of great significance to elevate the performance of cutting tools for titanium alloy[4].

WC-8Co cemented carbide is widely used in the field of metal cutting because of its high hardness and wear resistance[5]. Compared with newly developed materials for high-performance cutting tools targeting Ti6Al4V, it is more economical and feasible to improve the machining performance of the cutting tool for Ti6Al4V material through strengthening treatment. At present, the common technologies for tool strengthening are surface coating, heat treatment[6,7], etc. The electromagnetic coupling process is a new multi-physical field strengthening technique for tool material strengthening. This process is often used in metallurgy and metal modification. Compared with the coating strengthening treatment, electromagnetic coupling processing not only strengthens the metal surface, but also reinforces the internal tool. Compared with tool heat treatment, electromagnetic coupling processing has the advantages of a shorter processing time, higher efficiency, non-pollution, and lower cost, providing positive application prospects. Therefore, it has high research value.

Liu et al[8] found that electromagnetic processing techno-

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logy can reduce the side wear of tools by 35%, demonstrating a significant improvement in milling performance. Yip[9] found that through the magnetic field, the surface machining quality of titanium alloy parts improves, the bond wear, side wear, and machining vibration reduce, and the tool life improves. Wei et al[10] found that electromagnetic coupling processing can notably change the toughness and conductivity of the tool and improve its durability. Jiang et al[11] found that the increase of cutting speed is the main reason for the increase of cutting temperature and the tool oxidation wear in the experiment about the use of cemented carbide for dry turning of Ti6Al4V. However, there are few systematic and in-depth studies on the mechanism of the tool wear performance of electromagnetic-treated carbide cutting titanium alloy.

In this study, WC-8Co tools treated under different electromagnetic coupling processing parameters were used to investigate the corresponding cutting force, cutting heat signal, and wear of the flank surface of the tool during the dry turning of Ti6Al4V under the same cutting conditions. The friction coefficient of the tool before and after electromagnetic coupling processing was measured by a friction abrasion testing machine. The morphology and element analysis near the cutting edge before and after cutting were inspected by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). The cutting performance and wear behavior mechanism of WC-8Co cemented carbide tools before and after electromagnetic coupling processing were analyzed. The results provide theoretical support for further development of electromagnetic coupling field technology.

1 Experiment

1.1 Pulsed electromagnetic coupling processing

An electromagnetic coupling device is mainly composed of a capacitor discharge system and an excitation coil. The peak current during discharge is controlled by the charge saturation of the capacitor bank, so it can control the magnetic field intensity. The magnetic pulsed frequency can be controlled by the discharge rhythm of the capacitor bank.

The carbide tool to be processed was placed in the working cavity of the excitation coil in the electromagnetic processing device, and the two sides of the cemented carbide tool were connected with the pulsed electric field circuit. Then the electromagnetic processing device was switched on to apply the pulsed electric field and the pulsed magnetic field with the parameters shown in Table 1 to the cemented carbide tool. As shown in Fig.1, a pulsed magnetic field with a magnetic field strength of H and a pulsed current I in the same direction as magnetic field was applied to the cemented carbide tool.

1.2 Cutting experiment

The material of the workpiece in this experiment was Ti6Al4V, which is a titanium alloy with a microstructure of $\alpha+\beta$. Its main mechanical properties are: elongation δ>13%, tensile strength σ_b>980 MPa, yield strength $\sigma_{0.2}$>980 MPa, modulus of elasticity E>115 GPa, and the hardness is HRC=37. The Ti6Al4V titanium alloy bar used in the tests had a length of 300 mm and a diameter of 60 mm. Its chemical composition is shown in Table 2. The model of the selected tool is 31303C, and its geometric parameters are front angle γ_0=6°, rear angle α_0=90°, auxiliary rear angle α'_0=7°, main deflection angle K_r=90°, transition edge width of 0.2 mm, and chip discharge groove width of 5 mm. The platform for the turning experiment is shown in Fig.2. A CAK6152 numerical control lathe was selected as the experimental lathe. The cutting parameters are cutting depth a_p=0.25 mm, feed speed f=60 mm/min, and cutting speed v=75 m/min. The multicomponent force measuring system (Switzerland Kislter9257B) was selected as the force measuring system. A K-type thermocouple was adopted to measure the cutting temperature. As shown in Fig.3, the thermocouple was fixed in a rectangular groove with the same distance of the auxiliary rear cutter face

Table 1 Parameters of pulsed electromagnetic coupling processing for tool

Treatment	Magnetic field parameter			Pulse current parameter		
	Intensity/T	Frequency/Hz	Pulse number	Voltage/V	Frequency/Hz	Pulse number
Tool-0	-	-	-	-	-	-
Tool-1	1.5	1.0	20	1.2	50	250
Tool-2	1.0					

Table 2 Chemical composition of Ti6Al4V materials (wt%)

Al	V	Fe	C	N	O	Ti
5.5~6.75	3.5~4.5	≤0.30	≤0.10	≤0.015	≤0.20	Bal.

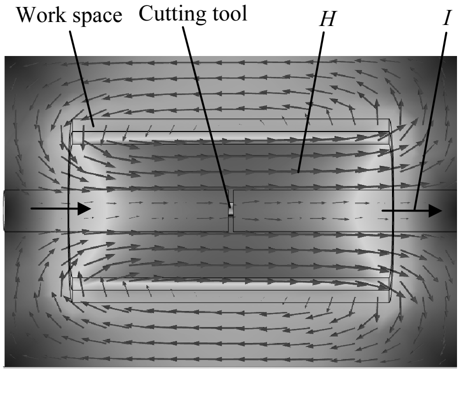

Fig.1 Schematic of sample position in electromagnetic field

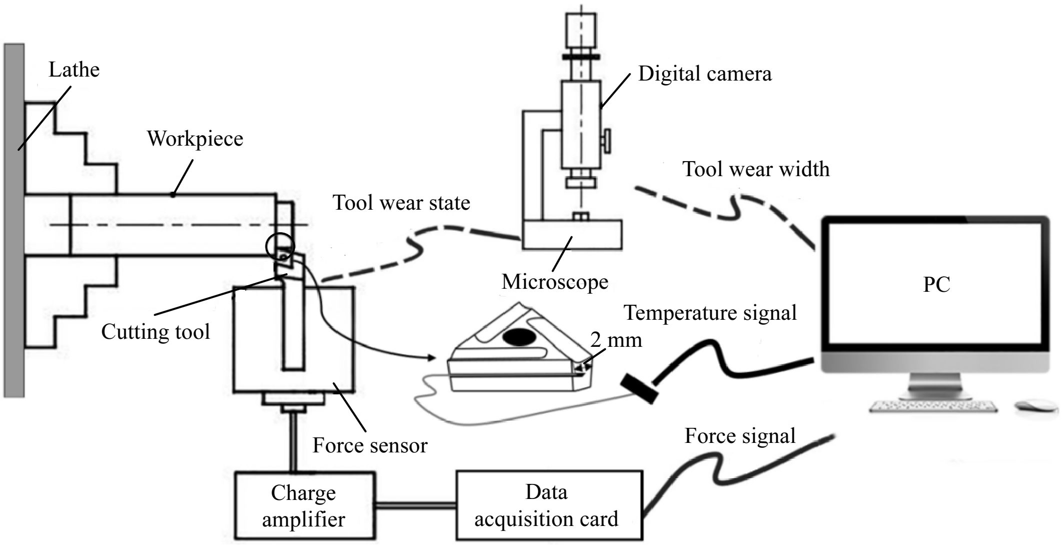

Fig.2 Mode of turning experiment

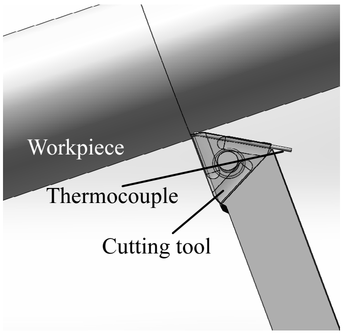

Fig.3 Measurement model of cutting temperature

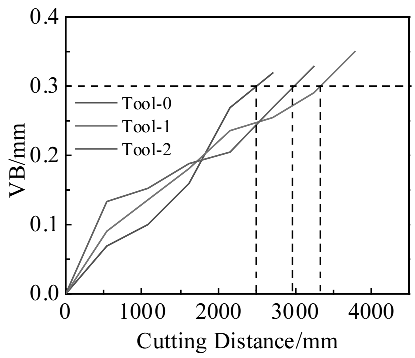

Fig.4 Tool wear of different electromagnetic coupling parameters

to collect the temperature signal[12]. After a machining time of 180 s, the wear width of the tool was measured using an optical microscope.

2 Results and Discussion

2.1 Tool life

The life of the tools is the service time from the beginning of cutting until the cutting tool reaches the tool blunt standard, which is an important index to measure the cutting performance. According to the relevant technique and the international standard for the machining of Ti6Al4V with WC-8Co cemented carbide, the wear condition of the flank surface of the tool, i.e., VB=0.3 mm, was selected as the tool blunt standard. The tool life curve with different electromagnetic processing parameters was obtained, as shown in Fig.4. Through the comparative analysis, the life of Tool-1 and Tool-2 improves in varying degrees after electromagnetic processing. Compared with the life of unprocessed Tool-0, the life of the tools after electromagnetic processing increases by 10%~36%. Tool-1 has the longest life, which is 36% longer than that of Tool-0 without processing.

2.2 Mechanical and physical properties

The hardness and fracture toughness of the WC-8Co cemented carbide materials with different electromagnetic coupling processing parameters were measured by a Rockwell microhardness tester. As shown in Table 3, the average values were calculated by measuring 15 samples under different process parameters in each group. The results show that the hardness of the tool materials treated by pulsed electromagnetic coupling changes and even slightly decreases, while the fracture toughness of the WC-8Co material increases by 14%~20% after it was treated by pulsed electromagnetic coupling. This is because the resistance of the material matrix enhances for the initiation, and the surface crack propagation reduces under fixed external load[13].

To characterize the friction state between the flank surface and the workpiece material during the cutting process, the friction coefficient tests for the Tool-1 and untreated Tool-0 were performed by a wear and abrasion test machine. Considering the high-temperature feature of Ti6Al4V, which makes it easy to change the friction performance of the friction pair, the friction pair was changed to mutual grinding of the high-speed steel material and the WC-8Co material ball. The friction coefficient measured under a load of 200 N is shown in Fig.5. The friction coefficient of the untreated Tool-0 of WC-8Co is approximately 0.5, while that of the treated Tool-1 of WC-8Co is about 0.3. This shows that the friction coefficient of the materials reduces by the pulsed electromagnetic coupling processing. The fluctuation of the friction coefficient of the latter in the entire friction test is also more stable. This can be related to the greater temperature fluctuation induced by the higher friction coefficient of the former.

2.3 Cutting mechanism

Cutting force is an important physical quantity in the cutting process. It can effectively reflect the stability of the cutting process and the machinability of the tool[14]. Fig.6 shows the trend of the resultant cutting force applied by the cutting tools processed under different pulsed electromagnetic coupling parameters with increasing the cutting distance. The resultant cutting force of Tool-1 and Tool-2 treated by the electromagnetic coupling processing is far less than that of the untreated Tool-0.

With the increase of the cutting distance, the cutting force increases in different degrees. This is due to not only the decrease of the friction coefficient between the flank surface and the workpiece, but also the increase of the extrusion and friction of the wear edge formed by the larger wear of the flank surface.

Moreover, the cutting force can be used to analyze the two-

Table 3 Properties of the tool samples

Properties	Tool-0	Tool-1	Tool-2
Hardness/MPa	1460	1442	1455
K_{IC}/MPa·m$^{1/2}$	13.49	15.58	14.59

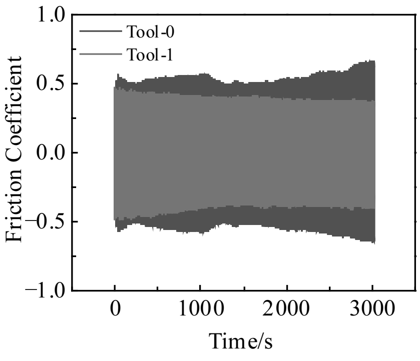

Fig.5 Friction coefficient of tool with different treatment parameters

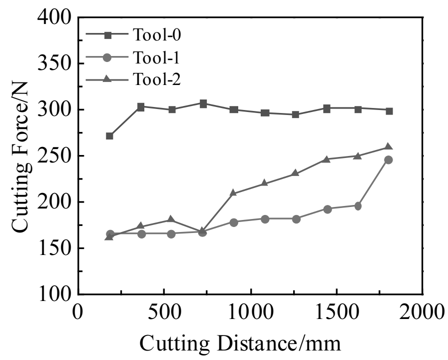

Fig.6 Resultant cutting force of different tool samples

phase friction coefficient of the cutter-chip on the front face. The cutting process of the front face area is mainly caused by chip flow friction, so the friction coefficient of the front face can effectively reflect the cutting condition. According to Eq.(1), the ratio of the cutting depth resistance F_y to the main cutting force F_z is equal to tan($\beta+\gamma_0$). By the known rake angle γ_0 of the tool, the friction angle can be acquired, and the average friction coefficient of the front face is equal to tanβ[15].

$$F_y/F_z = \tan(\beta+\gamma_0) \tag{1}$$

Table 4 shows the calculated two-phase friction coefficient of the front face of the tool after applying the pulsed electromagnetic coupling. It is clear that the two-phase friction coefficient of the tool-chip of the front face after processing is higher than that of the unprocessed tool. Fig.7 shows the result of the cutting temperature on the auxiliary flank surface collected by the thermocouple temperature measurement system. The cutting temperature of the untreated tool is significantly higher than that of the processed tools because of the friction coefficient between the tool and the workpiece. Moreover, the decrease of the cutting temperature results in the reduction of chip plasticity and the increase of flow stress[16]. This leads to the increase of the two-phase friction coefficient of the tool-chip two-phase on the front face.

2.4 Wear mechanism analysis

Fig.8 shows SEM images of the flank surface of different tool samples after the same cutting experiment. The patterns of the tool wear are shown as well. At different degrees of wear of the front face, the flank surface and boundary are observed, accompanied by microchipping and surface bonding. Sharp friction occurs between the front faces and the chips as well as the main flank surfaces and the machining surfaces, resulting in the high contact pressure and temperature. This induces wear on the front face, main flank surface, and boundary of the tool. In the cutting areas, including the front

Table 4 Friction coefficient of the front face of the tool samples

Tool-0	Tool-1	Tool-2
0.46	0.89	0.71

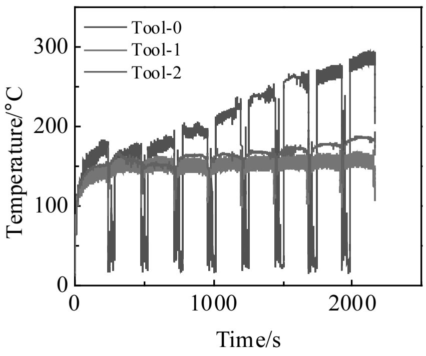

Fig.7 Cutting temperature of different tool samples

knife surface, rear knife surface, and tip, the attrition loss of Tool-0 is obviously greater than that of the electromagnetically treated Tool-1 and Tool-2. This phenomenon is closely related to the previous mechanical property experiment of WC-8Co: after different electromagnetic treatments, the bonding performance of the Co phase in the tool material improves because of the magnetoplastic[16,17] and electroplastic[18] effects, thus increasing the toughness of WC-8Co. Therefore, the shedding phenomenon of WC reduces because the remnants of Co increase after cutting, which reduces tool wear. The experimental data show that the toughness improvement of Tool-1 after electromagnetic treatment is better than that of Tool-2. This result is also verified by other relevant experimental data (cutting temperature and cutting force).

Ti6Al4V has high chemical activity and a strong affinity with the tool. During the cutting process, titanium alloy chips become stuck on the tool. As cutting progresses, the chip bonded particles remove, resulting in the sticking wear of the tool. In addition, in the process of the dry turning of Ti6Al4V, the high temperature at the cutting area cannot be transferred away because of the low thermal conductivity of the workpiece. The hot WC-8Co material contacts the air and then produces oxides with poor mechanical properties, leading to the wear on the tool.

Fig.9 shows the SEM wear morphologies and EDS spectra

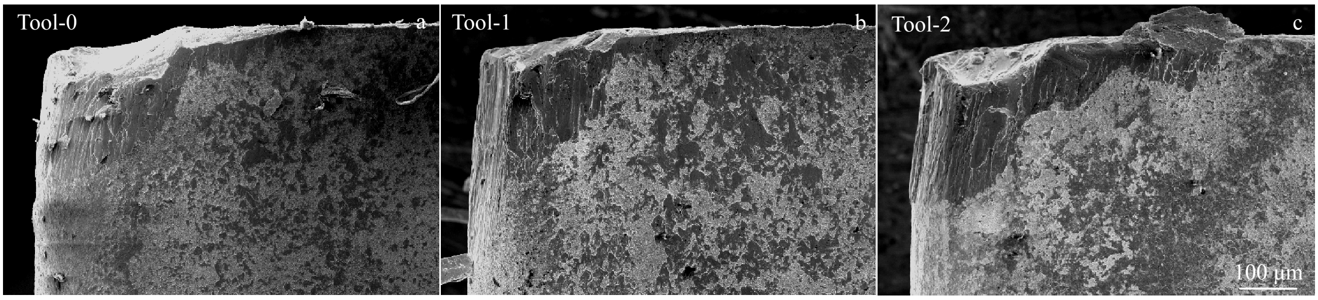

Fig.8 SEM images of the flank surface of different tool samples after cutting test: (a) Tool-0, (b) Tool-1, and (c) Tool-2

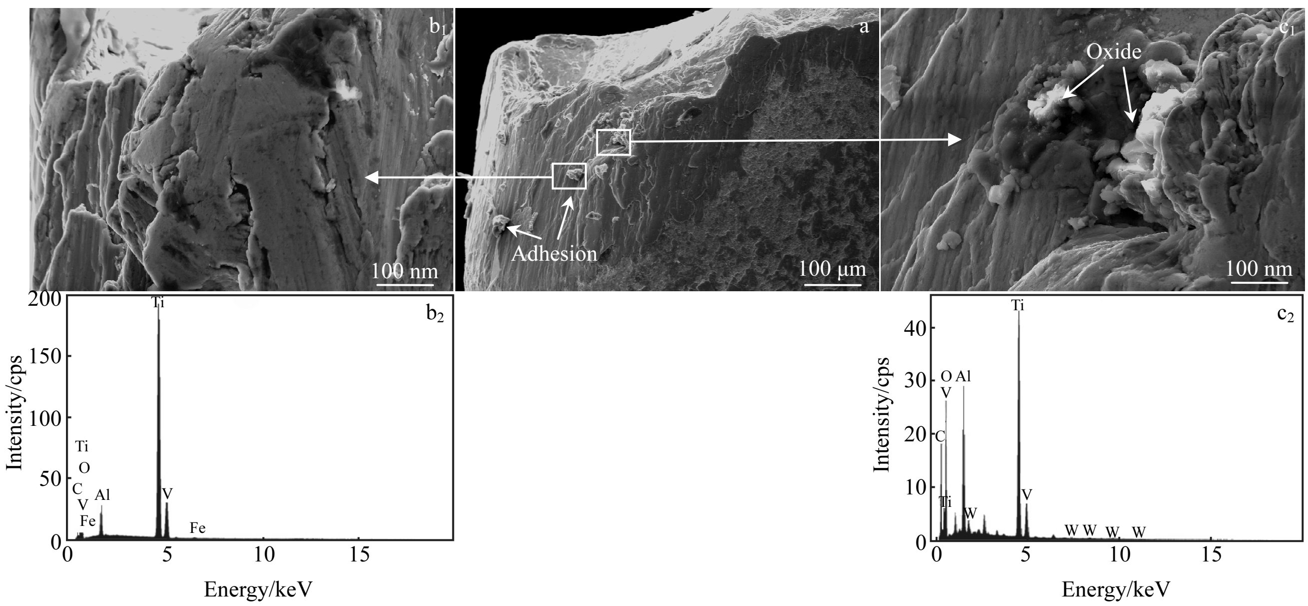

Fig.9 SEM images of wear morphology (a, b_1, c_1) and EDS analysis (b_2, c_2) of the flank surface of Tool-0

of the flank surface of Tool-0. It is clear that Ti is mainly attached to many areas of the cutting part of the tool. This indicates that the main wear form of WC-8CO cemented carbide in the dry turning of Ti6Al4V is binding wear. In addition, because of the high temperature in the cutting area of the untreated Tool-0, bright white solid substance attachment appears. EDS test for this area reveals that the oxygen content of these solid bright white substances is much higher than that of other areas. Moreover, this phenomenon cannot be observed at the wear areas of Tool-1 and Tool-2 after electromagnetic treatment.

In this phenomenon, the surface oxidation wear of the WC-8Co treated by electromagnetic coupling reduces compared with that of the untreated tool. In addition, EDS detection also found aluminum and vanadium in the tool wear area, which should be in the workpiece material Ti6Al4V. Tungsten and cobalt are rarely detected in the wear zone, indicating that elements in the workpiece diffuse during cutting under high temperature and pressure conditions. The wear forms of the WC-8Co carbide tool in dry turning Ti6Al4V are mainly adhesive wear, oxidation wear, and diffusion wear, while electromagnetic coupling treatment can change the proportion of each wear form.

Table 5 shows the mass fraction of the elements in the cutting area of tool processed under different electromagnetic coupling parameters. Fig.10 shows the EDS mapping. The oxygen content in the cutting area of the WC-8Co tool after pulsed electromagnetic coupling processing significantly reduces, decreased by 58.7%~65.7%. The untreated tool has obvious oxygen enrichment in the wear area of the flank surface. Therefore, the oxidation resistance of the WC-8Co tool processed by pulsed electromagnetic coupling effectively enhances, i.e., the oxidation wear of the tool reduces. According to the previous discussion in this research, the friction coefficient of the flank surface of the WC-8Co tool after pulsed electromagnetic coupling processing decreases, and it leads to a decrease of the cutting temperature. Meanwhile, the cutting temperature of the Ti6Al4V dry turning process directly affects the physical quantity of the oxidation wear of the tool. Therefore, the wear performance and the durability of the tool improve. At the same time, the Co content of the tool after the treatment also changes compared with that of the untreated tool. The WC-8Co tool after pulsed electromagnetic coupling processing has Co enrichment in the wear area of the flank surface, while the distribution of Co in the untreated tool is relatively sparse. The wear of the WC-8Co tool is often caused by the loss of Co, which leads to a poor cobalt state of the tool and the falling-off of hard-phase WC. This also

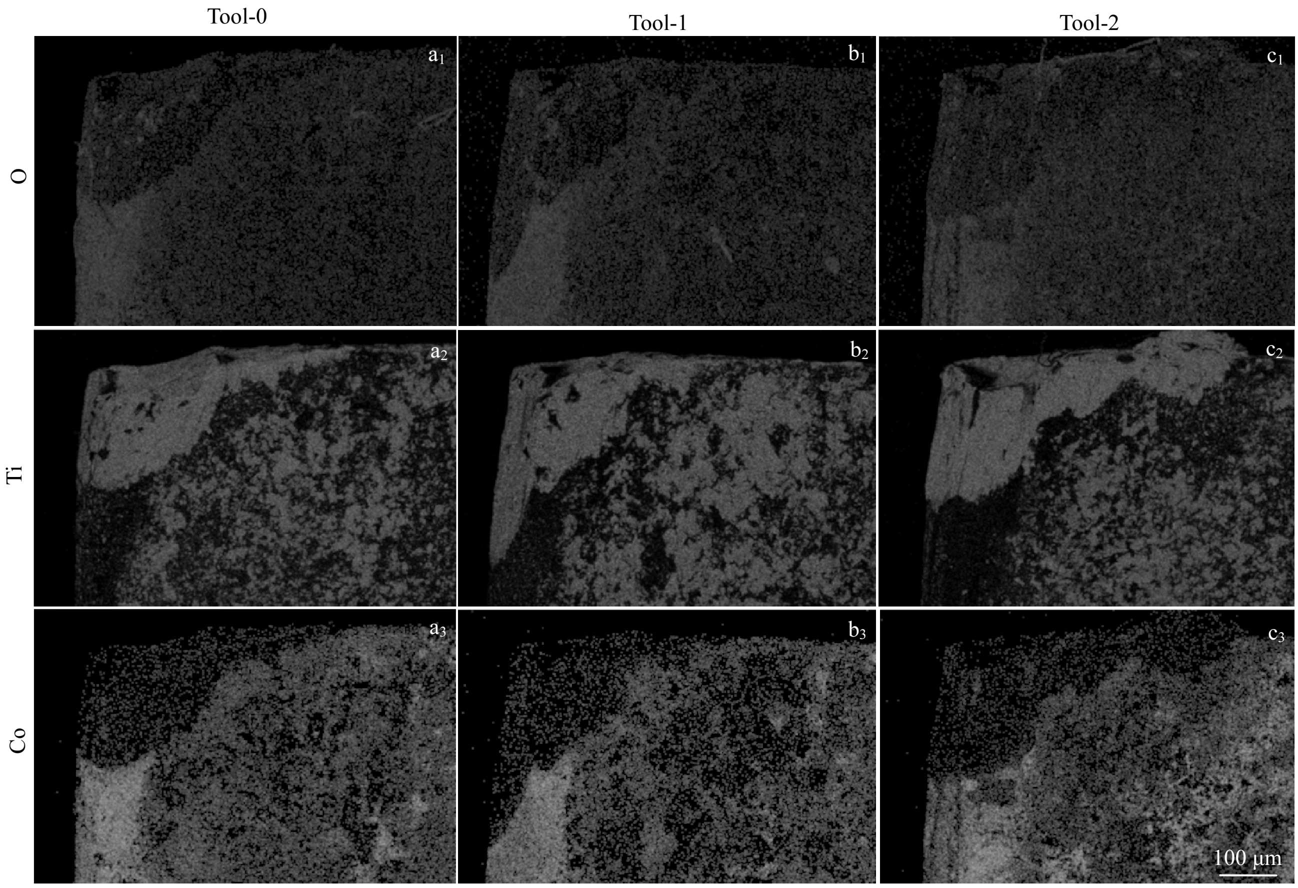

Fig.10 EDS mapping of wear area of different tool samples: (a_1~a_3) Tool-0, (b_1~b_3) Tool-1, and (c_1~c_3) Tool-2

Table 5 Element mass fraction in the cutting area of different tool samples (wt%)

Sample	Ti	Al	V	W	O	C	Co
Tool-0	48.87	2.97	8.15	0.35	38.86	0.78	0.02
Tool-1	69.04	4.81	5.59	2.55	13.26	1.86	2.89
Tool-2	66.39	5.36	5.39	2.42	16.36	1.99	2.09

explains why the tool has better wear performance after pulsed electromagnetic processing.

3 Conclusions

1) Compared with the life of the unprocessed tool, the life of the tools after electromagnetic processing increases by 10%~36%. Tool-1 has the longest life, which is 36% longer than that of Tool-0 without processing.

2) The fracture toughness of the WC-8Co tool increases by 20% after pulsed electromagnetic coupling processing. The microchipping edge decreases, and the remnants of Co increase after cutting. However, the hardness of the tool does not increase significantly, showing that pulsed electromagnetic coupling processing can strengthen the bonding phase Co while the shedding phenomenon of WC reduces.

3) The main wear forms of the pulsed electromagnetic coupling processed tool are adhesive wear, oxidation wear, and diffusion wear. However, pulsed electromagnetic coupling processing can effectively reduce the friction coefficient of the tool, resulting in a decrease in cutting temperature and oxidation wear of the tool by 58.7%~65.7%, thereby improving the machinability of the turning of Ti6Al4V.

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脉冲电磁耦合处理前后 WC-8Co 硬质合金干车削 Ti6Al4V 的切削机理

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摘　要：利用脉冲电磁耦合处理设备对 WC-8Co 硬质合金进行强化处理。通过测试 WC-8Co 力学及摩擦性能，再利用采集车削试验中的切削力、温度及后刀面磨损量信号对干车削 Ti6Al4V 的切削行为进行了分析。最后采用 SEM 和 EDS 对 WC-8Co 硬质合金进行观测与分析，得出脉冲电磁耦合处理前后 WC-8Co 硬质合金干车削 Ti6Al4V 切削机理。结果表明：脉冲电磁耦合处理能够提升刀具耐用度，降低切削温度及刀具后刀面氧化磨损。

关键词：脉冲电磁耦合；WC-8Co 硬质合金；Ti6Al4V；切削机理

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