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Research Article

Experimental Study on Electrode Wear of Diamond-Nickel Coated Electrode in EDM Small Hole Machining

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Aiming at the problem of obvious tool length wear and side wear in the small hole processing of EDM, the nickel-coated composite electrode and diamond-nickel-coated composite electrode were prepared by chemical composite coating using brass, copper, molybdenum, and copper-tungsten alloy materials as the matrix material. Comparative experiments of EDM small hole machining using composite tools were carried out on die steel. The effects of nickel-coated composite electrode and diamond-nickel-coated composite electrode on tool length wear, tool side wear, and tool shape change were analyzed. The results show that the diamond-nickel-coated composite electrode can effectively reduce both the length wear and side wear of the electrodes.

1. Introduction

Electrical discharge machining (EDM) is a nontraditional machining method, and its material removal principle is to melt and vaporize a small amount of metal by the instantaneous high temperature generated during pulsed electric discharge. It has unique advantages of noncontact processing, no limitation on material strength and hardness, and high machining precision so that it is more and more widely used for high-efficiency precision machining and micromachining of difficult-to-machine materials in the aerospace, transportation, and mold manufacturing industries [1–3]. In addition, EDM is also indispensable in microhole machining, fine 3D structure milling, and precision mold manufacturing [4–6]. However, the significant electrode length wear and side wear during the EDM hole machining seriously affect the machining accuracy of the electrode. Therefore, exploring the methods of improving tool length wear, side wear, and machining quality in EDM has been a hot topic widely studied by many scholars. In the process of EDM, Cao et al. fabricated a Cu-Cr composite tool for the problem of rapid reduction of material removal rate and conducted a comparison experiment of EDM with brass tool and Cu-Cr composite tool. The experimental results show that the material removal rate of composite tools increases about 2 times and the processing precision is also improved [7]. El-Taweel studied the Al-Cu-Si-TiC composite tool produced by powder metallurgy technology and processed it for processing analysis. It is found that the Al-Cu-Si-TiC tool is more sensitive to peak current and pulse conduction time than the conventional tool and the percentage of TiC based on the optimal demand of the composite is 18% [8]. In order to prevent tool loss, Hai-Liang and Cao proposed a method of processing small hole machining by EDM using dispersant dielectric fluid. The results showed that the reasonable choice of the composite tool and dispersant dielectric fluid could effectively improve the processing speed, lower tool wear, and improve depth-to-diameter ratio of the drilling hole significantly [9]. Tsai et al. proposed a new method of blending the copper powders containing resin with chromium powders to form tools. Such tools are made at low pressure (20 MPa) and temperature (200°C) in a hot mounting machine. The results showed that using such tools facilitated the formation of a modified surface layer on the electrode after EDM, with remarkable erosion resistance properties. And the composite tools obtained a higher material removal rate than Cu tools [10]. Teng studied the electroplating preparation process of the Cr-Cu composite tool. Based on this, the brush plating preparation process of the composite tool was proposed, and the rotating brush plating device was made and carried out in experiments [11]. Lv prepared a new copper-based nickel-tungsten alloy composite tool by the nickel-tungsten co-deposition electroplating method and carried out microhole machining experiments. The results showed that the nickel-tungsten alloy coating has good erosion resistance performance, which can effectively reduce the side wear of the tool, especially at the end and edge, maintaining the shape of the tool and improving the shape precision of the machined microhole [12]. Zhang used the gel comprised mixture of TiN-Cu powders sodium alginate dispersant and gelatin binder and concluded that the wear rate of the tool is lower than that of the copper tool [13]. Lei et al. proposed a wear-variation EDM (WV-EDM) approach to fabricate a laminated disc electrode (LDE) with stable-shape microchannels on the outer edge surface. This electrode was subsequently used to machine microgrooves on workpieces by EDM, and it is concluded that this tool could promote the machining efficiency [14]. According to the above research, although the current researches on composite tools have achieved rich results, due to the numerous methods for preparing composite tools, the influence of composite tool wear and shape change remains to be further studied.

In this paper, in order to reduce the significant problem of tool length wear and side wear in EDM, tools of the nickel layer and diamond-nickel layer based on brass, copper, molybdenum, and copper-tungsten alloy materials as the matrix material were made by chemical composite coating. Comparison experiments of composite tools in EDM were made, and die steel was used as the workpiece. The effects of the composite tools on tool wear, tool shape change, and machining accuracy were analyzed. It provides a new tool preparation method for EDM, and the research results have certain guiding significance for the actual production in EDM.

2. Principle of EDM with Composite Tool

Length wear and side wear of the tool occur during EDM, which is mainly caused by the tip concentration of electric field intensity and "secondary discharge" of the debris [15, 16]. The surface of the tool is coated with an erosion resistant material, the composite tool prepared by the coating process in which can effectively reduce the wear of the tool end and suppress the shape change of the tool end. The erosion resistance of the coating material can be expressed by the following equation [17]:

$$K = C\lambda\rho T^2, \tag{1}$$

where K is the erosion resistance exponent, C is the specific heat, λ is the thermal conductivity, ρ is the density of the coating material, and T is the melting point of the coating material. Figure 1 is a schematic diagram showing the processing wear of a common tool and a composite coating tool. The common tool is the noncoated tool.

The material removal of the composite tool in the initial stage is the same as that of the common tool. During the processing, due to the existence of the erosion resistance coating, the material removal of the length tool is relatively smaller than that of the common tool in a single discharge and the side wear of the tool is also relatively reduced, which reduces the wear of the tool and improves the shape accuracy in EDM to some extent [18–20].

3. Composite Tool Preparation and Experimental Design

3.1. Preparation of Composite Tool Coating. In order to reduce tool wear and improve machining accuracy, the composite tool is prepared by chemical composite coating, and electrical erosion resistance material was coated on the surface of the matrix material [21–25]. Chemical composite coating flow diagram is shown in Figure 2.

The chemical composite coating experiment consists of three parts: pretreatment of the tool, coating solution, and postprocessing. The tool is processed with grinding, ultrasonic vibration degreasing, and hydrochloric acid cleaning activation, so it is free from pollution. The pretreatment degreasing parameters are shown in Table 1.

The tool is positioned in the heated coating solution at 80°C as shown in Table 2; for the diamond coating solution, the diamond is added and the solution is kept stirring to prevent the diamond from sinking to the bottom [26–29]. Then, the tool is positioned in a drying box at 180°C and kept heated for two hours so that the coating layer does not fall off easily and the hardness of the chemical composite coating layer is remarkably enhanced [30–32]. Therefore, by controlling the coating time, various materials are coated on the surface of tools and ensured that the coating thickness is over 10 μm.

3.2. Experimental Setup. The SEM machine used in the experiment is JSM 6360-LV. The specifications of SEM are shown in Table 3.

The DC power supply for electrolysis used in the experiment is PS3005. The specifications are shown in Table 4.

3.3. Experiment Design. In order to analyze the influence of wear and shape change of the common tool and nickel-coated composite tool as well as the diamond-nickel-coated composite tool, a flat-bottom cylindrical tool is used to make the composite coating tool, and composite tool experiments are carried out in EDM [33–36]. Table 5 shows the experimental parameters.

The physical properties of the materials are shown in Table 6.

In each set of experiments, the processing time was set to a fixed value, and the tool length before and after the processing was measured to calculate the tool wear. The shape of the end face of the electrode was observed by using an electron microscope, and the shape change of tools with different coating layers was analyzed. The diameter of tools and the diameter of the small holes were measured by using

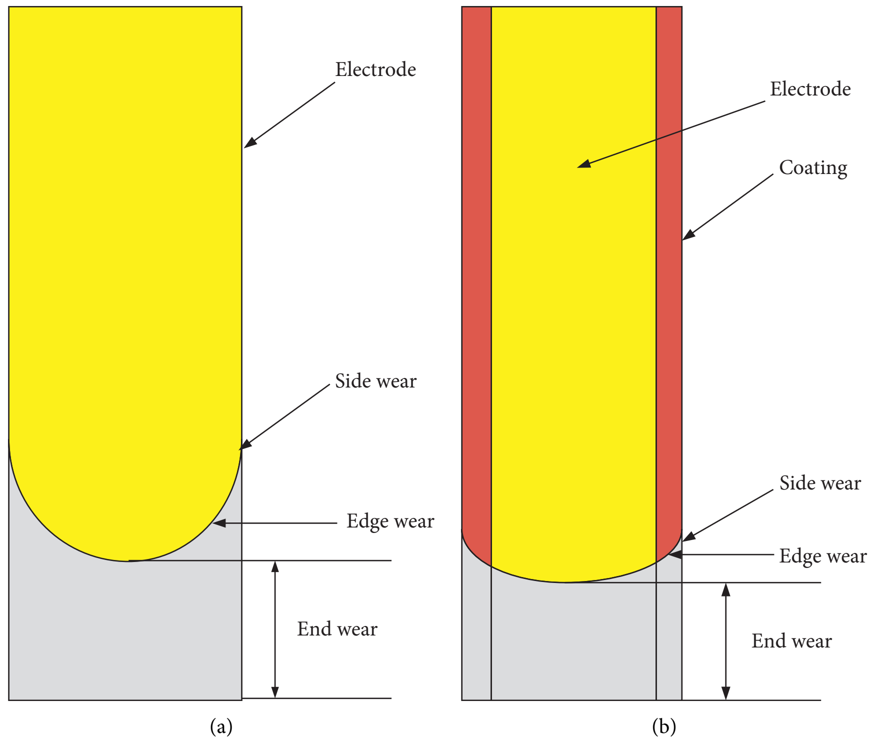


Figure 1: Comparison of (a) common tool wear and (b) coated tool wear.

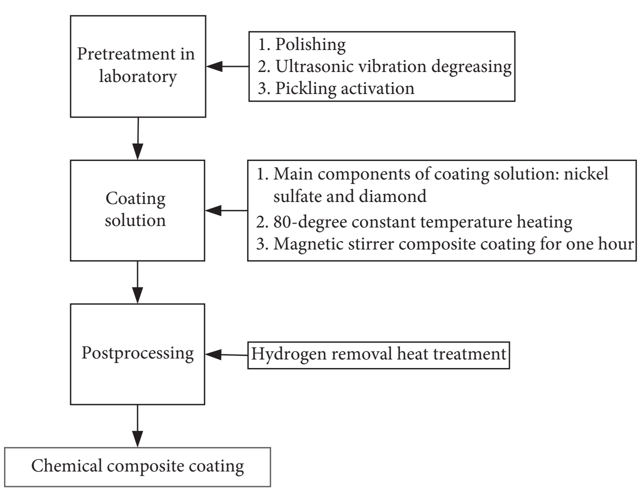


Figure 2: Chemical composite coating flow chart.

Table 1: Chemical degreasing parameters.

Solution composition and process conditions	Description
Sodium carbonate	15 g/L
Sodium phosphate	25 g/L
Sodium hydroxide	30 g/L
OP emulsifier	2 ml/L
Dodecyl sulfate	1 g/L
Temperature	$75 \pm 1^{\circ}$C
Time	20 min

Table 2: Ni coating solution.

Parameter	Description
Nickel sulfate	32 g/L
Sodium hypophosphite	32 g/L
Citric acid	5–10 g/L
Lactic acid	20–30 ml/L
Glycine	6–12 g/L
Succinic acid	10–20 g/L
Thiourea	1–5 mg/L
Sodium acetate	10–20 g/L
OP emulsifier	10–20 mg/L
Diamond	20 g/L
Temperature	$75 \pm 1^{\circ}$C
Time	20 min

Table 3: Specifications of SEM.

Parameter	Description
Resolution HV mode	3.0 nm (30 kV)
Resolution LV mode	4.0 nm (30 kV)
LV pressure	1 to 270 Pa
Accelerating voltage	0.3 kV to 30 kV
Specimen stage	X: 125 mm, Y: 100 mm, Z: 5 mm to 80 mm Tilt: -10° to $+90^{\circ}$, Rotation: 360°
Magnification	X5 to X100000

Table 4: Specifications of DC power supply for electrolysis.

Parameter	Description
Input	AC 220 V ± 10% 50 Hz ± 2 Hz
DC output	0.0–30.0 V, 0.00–5.00 A
Power	120 W
Resolution	100 mV, 10 mA

Table 5: Electrode experimental parameters in EDM.

Parameter	Description
Workpiece	Die steel
Electrode	Copper, brass, molybdenum, copper-tungsten alloy (W70) composite tool
Coating material	Nickel, diamond-nickel coating
Processing polarity	Positive polarity
Processing time	3 min
Pulse on	12.5 μs
Pulse off	7.5 μs
Discharge breakdown voltage	45 V
Peak current	0.8 A
Electrode diameter	2 mm
Working medium	Deionized water

the electron microscope, and the effect of working fluid concentration on machining accuracy was studied.

During the processing of EDM with composite tool, the coating material will have a corresponding influence on the tool side wear. The tool side wear of the small hole machining is calculated as follows:

$$\Delta D = \frac{D_1 - D_2}{2}, \quad (2)$$

where ΔD is the tool side wear, D_1 is the tool diameter before machining, and D_2 is the tool diameter after machining.

The wear rate is calculated as follows:

$$R = \frac{a - b}{a} \times 100\%, \quad (3)$$

where a is the material that has a large wear length and b is the material that has a lower wear length.

4. Results and Discussion

The EDM process uses the copy principle to obtain the machined shape. Therefore, the processed hole and the tool electrode have similar cross-sectional shapes. Since the hole cross section is not easy to observe, the cross section of the tool electrode in this paper approximates the cross section of the machined hole.

4.1. Composite Electrode Coating Observation. Figures 3(a)–3(c) show the common tool, the nickel-coated tool, and the diamond-nickel-coated tool, respectively. On the surface of the composite tools, the surface of the nickel-coated tool can be seen as bright silver white, indicating that the surface has been coated with a nickel layer. The diamond-nickel-coated tool surface not only becomes silvery white but also has some tiny particles, indicating that the surface of the tool has a different alloy layer.

The nickel-coated tool and the diamond-nickel-coated tool were observed by using SEM. Figure 4 shows the SEM images of the nickel-coated tool, where Figure 4(a) is the thickness image of the nickel-coated composite tool, Figure 4(b) is the local image of the nickel-coated composite tool, and Figure 4(c) is the spectrum analysis of the nickel-coated composite tool. It can be seen from Figure 4(a) that there is a coating layer on the copper tool and the preparation of the composite tool is excellent. According to the measurement, the thickness of the coating is about 13.84 μm, and a local coating layer is sampled to conduct an energy spectrum analysis; it can be seen that the main component of the coating is nickel and a small number of other elements.

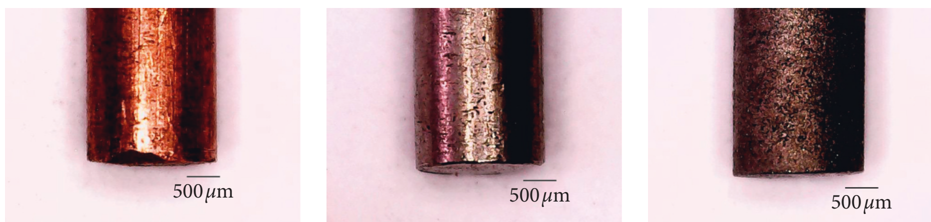
Figure 5 shows the SEM images of the diamond-nickel-coated composite tool, where Figure 5(a) is the thickness image of the diamond-nickel-coated composite tool, Figure 5(b) is the local image of the diamond-nickel-coated composite tool, and Figure 5(c) is the spectrum analysis of the diamond-nickel-coated composite tool. It can be seen from Figure 5(a) that there is an obvious coating layer on the copper tool. According to the measurement, the thickness of the coating is about 14.07 μm, and a local coating layer is sampled to conduct an energy spectrum analysis; it can be seen that the main component of the coating is diamond, nickel, and a small number of other elements.

4.2. Effect of Coating Materials on Tool Length Wear. The length before and after machining is measured by using optical image measuring instrument. Figure 6 shows the comparison of the length wear of the composite tools machined with positive polarity. It can be seen from Figure 6 that the tool length wear of the nickel-coated composite tool is lower than that of the common tool. The tool length wear of the nickel-coated composite tool was not significantly reduced compared with that of the common tool, while the diamond-nickel-coated composite tool was significantly reduced compared with the common tool. This is because nickel and diamond have an excellent thermal conductivity compared with the other materials. Nickel and diamond can reduce the length wear of the tool.

It can also be seen from Figure 6 that when the matrix material is brass or copper, the existence of the coating has a significant suppression effect on the tool length wear. For example, the tool length wear of the copper with diamond-nickel coating is about 30% lower than that of the common tool. However, when the matrix material is copper-tungsten alloy or molybdenum, the existence of coating has little effect on tool length wear. This is normally due to the fact that the electrical erosion resistance feature of nickel material is better than that of brass and copper, and the existence of the coating improves the electrical erosion resistance of the whole tools. After the diamond particles are added to the nickel coating, because the melting point of diamond is high and the heat capacity as well as thermal conductivity is excellent, the length wear of the diamond-nickel-coated tool is less. In addition, the heat in the tool can spread out

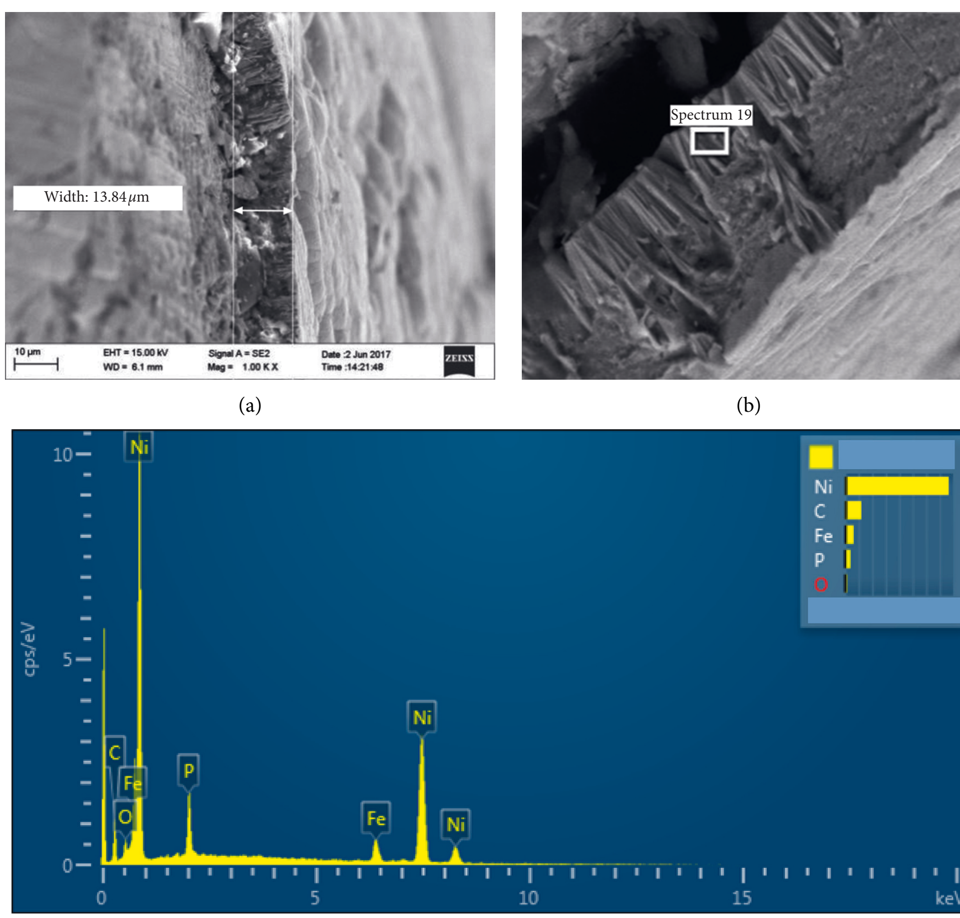
Table 6: Physical properties of materials.

Material	Melting point (°C)	Specific heat capacity (J/g·K)	Coefficient of thermal conductivity (W/m·K)	Electrical conductivity (S/m)	Work function (eV)
Brass	967	377	108.9	1.67×10^7	3.34–5.24
Copper	1083	386	386.4	5.95×10^7	5.24
Copper-tungsten alloy	3000–3410	—	220	2.5×10^7	4.54–5.24
Molybdenum	2620	255	142	1.93×10^6	4.37
Nickel	1453	452.2	59.2	1.43×10^7	
Diamond	3550	399–472	2000	Almost nonconductive	



(a) (b) (c)

Figure 3: Composite tools. (a) Common copper tool. (b) Nickel-coated tool. (c) Diamond-nickel-coated tool.



(a) (b)

(c)

Figure 4: SEM image of the copper tool with nickel coating. (a) Thickness image of the composite tool. (b) Local image of the composite tool. (c) Local energy spectrum analysis of the copper tool.

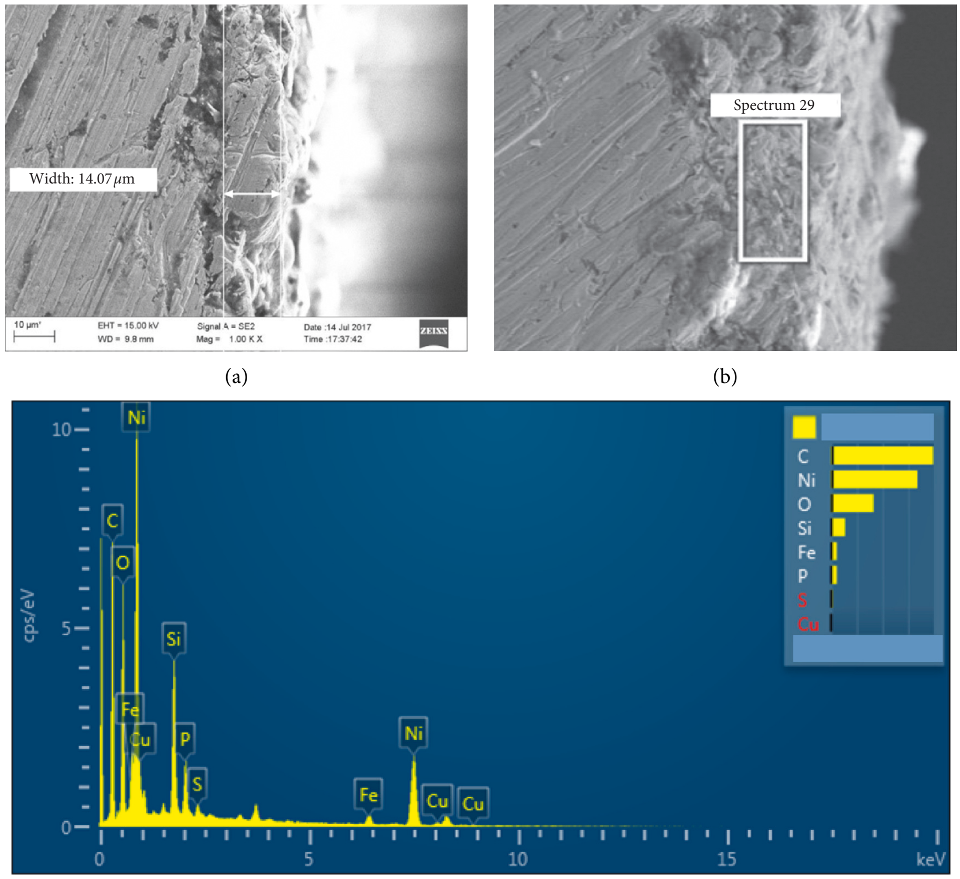


FIGURE 5: SEM image of the copper tool with diamond-nickel coating. (a) Thickness image of the composite tool. (b) Local image of the composite tool. (c) Local energy spectrum analysis of the copper tool.

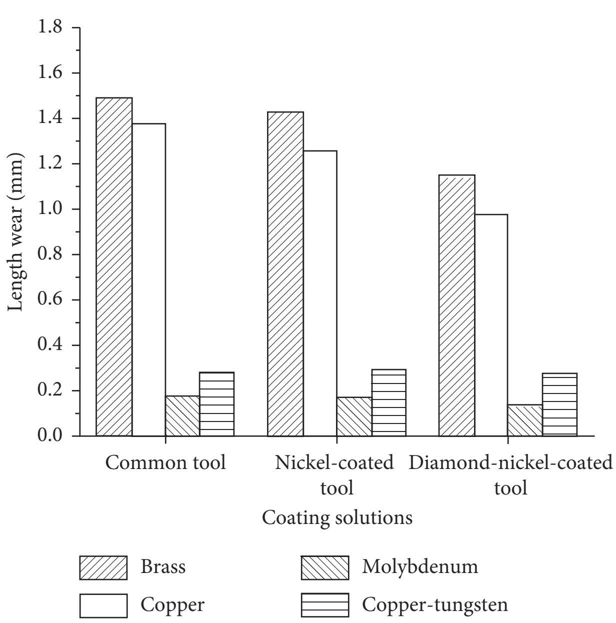


FIGURE 6: Length wear of different coated tools.

through the diamond particles during discharge, so the electrical erosion resistance of the diamond-nickel-coated tool is improved. The melting point and thermal conductivity of copper-tungsten alloy and molybdenum tools are higher, and the tools are not easy to wear. When nickel is coated on the tool surface, the melting point and thermal conductivity of nickel are not as good as that of copper-tungsten alloy. The erosion resistance of the whole tool is not obviously improved. The data in Figure 6 are shown in Table 7.

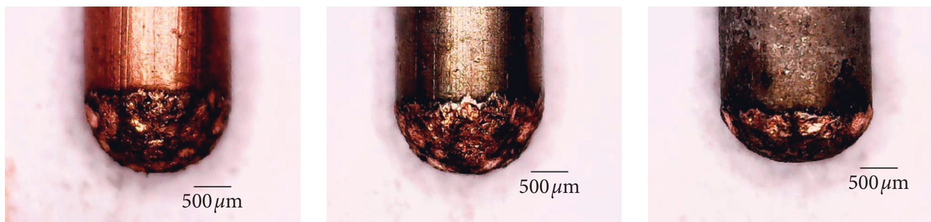
However, as the coating material increases the total mass of tools, it can be seen that the length wear of the tool will be reduced to a certain extent. And when the tool is coated with diamond-nickel, the melting point and thermal conductivity of diamond are much greater than that of the tool material. Due to the low wear and high thermal conductivity of diamond, the tool length wear of the coated tool will be significantly reduced.

4.3. Effect of Coating Materials on Tool Shape Change. Figures 7–10 show the shape changes of the common tool, nickel-coated tool, and diamond-nickel-coated tool with different matrix materials, respectively.

Figures 7 and 11, respectively, show the shape changes of brass-based and copper-based tools with positive polarity machining. It can be seen from Figures 7 and 11 that, from the common tool to the nickel-coated tool and to diamond-nickel-coated tool, the side of the tool wear is

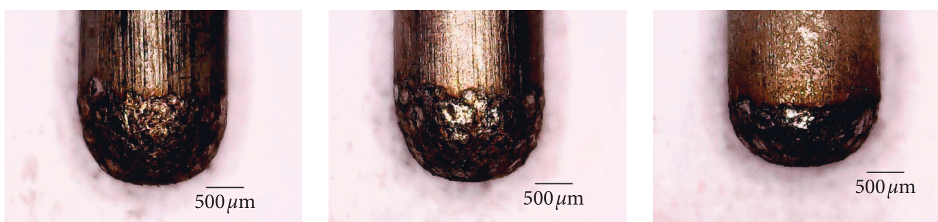
Table 7: Length wear of different coated tools.

Materials	Length wear (mm)		
	Common tool	Nickel coating	Diamond-nickel coating
Brass	1.492	1.432	1.145
Copper	1.384	1.211	0.984
Molybdenum	0.176	0.172	0.132
Copper-tungsten	0.281	0.273	0.266



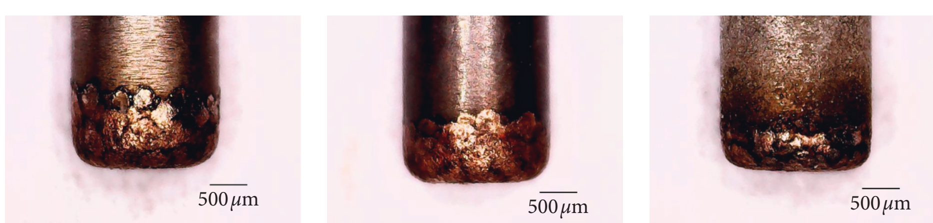
(a) (b) (c)

Figure 7: Shape change of copper-based composite tools. (a) Common tool. (b) Nickel-coated tool. (c) Diamond-nickel-coated tool.



(a) (b) (c)

Figure 8: Shape changes of molybdenum composite tools. (a) Common tool. (b) Nickel-coated composite tool. (c) Diamond-nickel-coated composite tool.



(a) (b) (c)

Figure 9: Shape changes of copper-tungsten alloy composite tools. (a) Common tool. (b) Nickel-coated composite tool. (c) Diamond-nickel-coated composite tool.

obviously reduced, and the end shape of the tool gradually changes from a hemisphere to a semiellipsoid so that the existence of coating reduces the side of the tool wear and improves the machining precision of hole shape to a certain extent.

This is mainly because the electrical erosion resistant material is coated on common tool surface, which can effectively reduce the tool material removal volume in the side discharge. When electrical erosion resistance of the coating is good, the suppression effect on the side wear of the tool will be obvious and the tool shape change is small. On the contrary, when the electrical erosion resistance of the coating is poor, the side wear of the tool is larger and the shape changes largely.

As shown in Figure 11(a), the tip of the tool is more rounded, so the wear is larger than Figure 11(c). Therefore, Figure 11(a) is more suitable for machining a shallow hole and Figure 11(c) is more suitable for machining a deep hole. Comparing Figure 11(c) with Figure 7(c), it can be seen that the copper-based tool is less rounded, which means that the copper-based tool shows lower wear and is better than the brass-based tool in machining a deep hole.

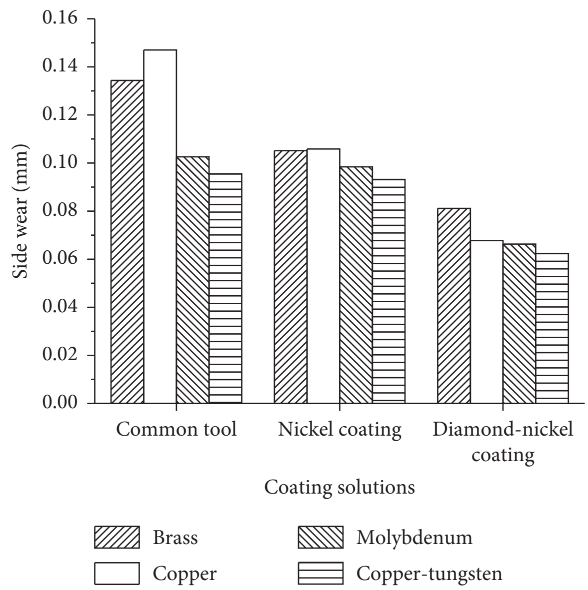


Figure 10: Side wear of different coated tools.

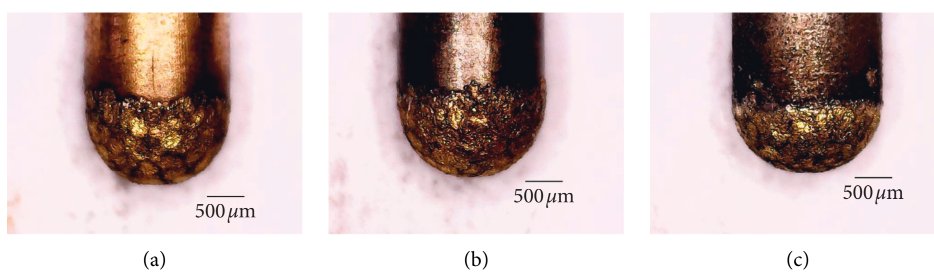


Figure 11: Shape change of brass-based composite tools. (a) Common tool. (b) Nickel-coated tool. (c) Diamond-nickel-coated tool.

Table 8: Side wear of different coated tools.

Materials	Side wear (mm)		
	Common tool	Nickel coating	Diamond-nickel coating
Brass	0.134	0.104	0.081
Copper	0.147	0.105	0.067
Molybdenum	0.102	0.098	0.066
Copper-tungsten	0.095	0.093	0.062

It can also be seen from Figures 7 and 11 that there is little change on the tool shape between common tool and nickel-coated tool. There are mainly two reasons: One is that the conductivity of nickel is similar to copper, resulting in similar electric field distribution. Second, the melting point and specific heat capacity of nickel are slightly higher than those of brass and copper, but the thermal conductivity is slightly lower than that of brass and copper so that the electrical erosion resistance of nickel, brass, and copper materials is similar, causing that the wear of nickel tool edge is similar to common tools. However, when the diamond-nickel-coated tool is used, the shape of the tool changes little after machining, which is mainly due to the very low electrical conductivity of diamond, making the electric field distribution uniform and not easy to form round corners. In addition, diamond has high thermal conductivity. The heat on the tool in the discharge process is quickly conducted away. Meanwhile, diamond has a high melting point, and there is a small material removal at the same discharge energy, resulting in a small side wear.

Figures 8 and 9 show the shape change of molybdenum and copper-tungsten alloy composite tools with positive polarity machining, respectively. It can be seen from Figures 8 and 9 that the shape of the nickel-coated tool has changed a lot rather than improving the side wear of the electrode, and this is mainly because molybdenum as well as copper-tungsten alloy electrode itself has a high melting point and high thermal conductivity, while the nickel-coated tool has a relatively lower melting point and thermal conductivity, and the electrical erosion resistance is worse and is easy to cause side wear in the discharge process, so the shape of the nickel-coated tool of molybdenum and copper-tungsten alloy varies much more greatly, which reduces the shape precision of the hole to a certain extent. When the diamond-nickel-coated composite tool is used, the tool shape change is little, and this is mainly because although electrical erosion resistance of molybdenum and copper is better than nickel coating, diamond-nickel composite coatings are doped with diamond particles with high melting point and thermal conductivity, making the tool side wear and length wear reduce accordingly. At the same time, the conductivity of the diamond material is low, which leads to the reduction of the probability of "secondary discharge" between the tool side and the hole wall. This is also the reason why the shape change of the diamond-nickel-coated composite tool is smaller than that of molybdenum and copper-tungsten alloy. Therefore, the diamond-nickel-coated composite tool can effectively reduce the side wear and improve the precision of the hole shape. Diamond helps reduce wear and improve the precision during processing in EDM.

4.4. Effect of Coating Materials on Tool Side Wear. Figure 10 is a comparison of tool side wear of composite tools in different tool materials and under different coating conditions. The diamond-nickel-coated tool shows the least wear due to the excellent thermal properties of diamond. The diamond has a high melting point and high thermal conductivity and is almost nonconductive, so the heat is easily conducted to other regions, and it is not easy to wear. The tool side wear of the nickel-coated composite tool is lower than the common tool. This is normally due to the fact that the electrical erosion resistance feature and melting point of nickel material are better than those of brass and copper, and the existence of the coating improves the electrical erosion resistance of the whole tools, so the wear of brass-based tool and copper-based tool is significantly reduced. The melting points of copper-tungsten alloy and molybdenum tools are higher than those of the copper and brass; therefore, the tools are not easy to wear. When nickel is coated on the tool surface, the melting point and thermal conductivity of nickel are not as good as those of copper-tungsten alloy. The erosion resistance of the whole tool is not obviously improved. The data in Figure 10 are shown in Table 8.

5. Conclusions

In this paper, the nickel-coated composite tool and the diamond-nickel-coated composite tool were prepared by chemical composite coating with brass, copper, molybdenum, and copper-tungsten alloys as matrix materials. The effects of the new composite tool on tool wear, the law of tool shape change, and machining precision were studied. The coatings could affect the machining accuracy of the hole. One is shape change, and the other is the reduction in length wear and side wear. Conclusions are as follows:

(1) The composite tools prepared by the chemical composite coating method are obtained, and the thickness of the coating layer was up to 13.82 μm, which met the processing requirements.

(2) The tool coating has a great influence on the tool wear. The wear of the diamond-nickel coating layer of brass, copper, molybdenum, and copper-tungsten material reduces than the nickel coating layer, reaching 23.49%, 28.99%, 26.14%, and 7.14%, respectively. However, the wear of the nickel coating layers only reduces 4.03%, 12.32%, 2.27%, and 3.57%, respectively.

(3) Nickel coating improves the wear of metal tools with poor electrical erosion resistance while increases side wear to tools with high electrical erosion resistance. Whether the property of the tool matrix material is good or not, the diamond-nickel coating can reduce the side wear of the tool to a certain extent and improve the shape precision of the EDM.

(4) When the material is brass or copper, whether the coating is nickel or diamond, the wear rate of the material is significantly improved. If the material is molybdenum or copper-tungsten, nickel coating improvement effect is not obvious, but diamond coating improvement effect is particularly good.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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