Study on Recast Layer Thickness of Microstructures Machined in micro-EDM with Different Electrodes

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Abstract

Functional-surface microstructures are widely used in industrial practice. During the fabrication of microstructures in micro-electrical discharge machining (micro-EDM), the thermal and physical characteristics of both workpieces and electrode materials at room temperature and high temperatures have an important influence on surface quality and distribution of recast layer. In order to study the influence of different electrode material characteristics on the surface integrity of microstructures machined using micro-EDM, red copper, brass, copper-tungsten and tungsten electrode were used to perform micro-EDM on both Ti-6Al-4V alloy and 304 stainless steel. In the experiment, electrode with groove arrays featuring high copying accuracy and surface quality was designed to carry out powder mixed electrical discharge machining (PMEDM) on Ti-6Al-4V alloy, and the machining results were evaluated based on four indicators: microstructure morphology, tool electrode wear (TEW), material removal rate (MRR), and recast layer thickness (RLT). Simultaneously, the surface morphology and recast layer thickness changes of 304 stainless steel workpieces machined using the above four types of electrodes, using both normal polarity and negative polarity micro-EDM were quantitatively analyzed. The results showed that copper-tungsten electrode is recommended to machine Ti-6Al-4V alloy because it has a smaller TEW (139 μm), the highest MRR (255.39 mm^3/min), and a thinner recast layer thickness (3.35 μm). This was followed by copper electrode, which featured good machining performance and machinability. When machining 304 stainless steel with negative polarity, the TEW of copper electrode and tungsten electrode was the smallest, and the thickness of recast layer was able to be effectively reduced to about 3 μm.

1. Introduction

Functional-surface microstructures possess the advantages of improved lubrication conditions, reduced friction, and enhanced heat dissipation performance, and have significant application value for practical industrial production [1–3]. Micro-EDM is one of the most common processes for fabricating functional-surface microstructures. However, surface machined using micro-EDM inevitably feature recast layer and micro-cracks. These disadvantages affect surface quality (Fig. 1a) and performance of the components, and in severe cases, it will cause the parts to fail [4–5]. As shown in the Fig. 1, on the surface of the titanium alloy workpiece after EDM, there are obvious recast layer, surface damage caused by micro-cracks and microporous (Fig. 1b). The combination of recast layer and base material is not reliable, and it is easy to cause peeling and accelerate wear. Therefore, it is necessary to try to eliminate recast layer.

Different material electrodes exhibit various wear rates in EDM. To make full use of such characteristic, *Lei et al.* [6] used copper, silicon, and copper-silicon alloy disc foils to construct a laminated disc electrode, and then used these electrodes to produce microgroove structures and micro-columnar structures on the titanium alloy workpieces. To obtain fine surface finish from their own micro-EDM processes, *Jahan et al.* [7] used tungsten, copper-tungsten, and silver-tungsten electrodes to fabricate WC, and found that silver-tungsten electrodes appeared to be the best choice to perform die-sinking micro-EDM of WC. The surface finish of these pieces was found to be greatly influenced by the electrical and thermal properties of the electrode material. In order to identify correlations between the material characteristics and the EDM processing results, four different grain sizes and five different cobalt contents were applied in S-EDM experimental analysis. The experimental studies showed the general suitability of tungsten carbide-cobalt tool electrodes for EDM [8].

There have been a number of studies performed by different researchers on the effect of different electrode materials on machining efficacy. *Lee and Li* [9] explored the effect during EDM of tungsten carbide using copper-tungsten, graphite, and copper electrodes. The effectiveness of these was evaluated in terms of the MRR, the TWR, and the surface quality. They concluded that copper-tungsten was the most suitable tool electrode for the EDM of tungsten carbide. *Hasçalık and Çaydaş* [10] used graphite, electrolytic copper and aluminum on Ti-6Al-4V to perform EDM. The experimental results showed that the surface recast layer processed by the copper electrode contained obvious micro-cracks. The graphite electrode featured improved MRR, TEW, and surface crack density, but relatively poorer surface finish. *Boujelbene et al.* [11] analyzed the effect of machining parameters on the surface characteristics of X200Cr15 and 50CrV4 using copper and graphite electrodes during EDM. The results showed that, with a lower pulse duration and a lower discharge current, a thinner recast layer thickness and heat affected zone (HAZ) can be achieved, and MRR will be reduced. *Khan et al.* [12] studied the surface characteristics of machined Ti-5Al-2.5Sn using copper-tungsten, copper, and graphite electrode. They reported that at low discharge energy, the copper-tungsten electrode produced the finest surface structure whilst graphite delivered worst surface characteristics. They also used these three types of electrodes to process Ti-5Al-2.5Sn titanium alloy with reverse polarity, and the results showed that among them, the copper electrode produced the lowest *Ra* whilst graphite electrode produced the highest [13]. *Choudhary et al.* [14] developed a new model for EDM-processed stainless steel 316 machined by copper, brass, and graphite electrodes, they revealed that MRR was higher for copper electrode compared to brass. Brass provided a better surface quality than copper electrode. *Büttner et al.* [15] explored the key factors of micro-features of electrodes which have to be considered in the micro-milling of pure copper and tungsten-reinforced copper. *Bai et al.* [16] found that, when using brass and copper electrode to process 45-carbon steel and W18Cr4V, brass electrode were able to achieve higher MRR compared to copper electrode. *Munmun and Kalipada* [17] used copper, brass, and zinc electrode subjected to electrical discharge machining of Ti-5Al-2.5Sn titanium alloy, comparing the machining results, it was found that thinner and more uniform recast layer and higher surface crack densities were found on surfaces which had undergone EDM surface machining by copper electrode, as compared to brass and zinc electrode. Therefore, they recommend using copper tool electrode in EDM products which require higher precision and superior surface finish. *Carlini et al.* [18] researched the influence of two different grades of copper-tungsten (CuW) electrode with 65% and 85% volumes of EDM cemented tungsten carbide. Based on the results, the CuW85 electrode presented lower TEW and higher MRR than that of CuW65 electrode. It was also found that there were obvious micro-cracks stretching from recast layer to HAZ. *Selvarajan et al.* [19] studied micro-EDM processing of SS316 material using copper and graphite electrode, and the results showed that graphite electrode performed better in this scenario. *Raza et al.* [20] studied the influence of three input parameters on the MRR, Ra, and EWR using copper, brass, and stainless steel electrode. Comparative analysis revealed the brass electrode as a superior option for MRR and Ra, while stainless steel was identified as a better alternative for EWR. The above study shows that the thermal physical characteristics of workpieces and electrode materials at room temperature and high temperature have an important impact on the machining results. Therefore, it is of great significance to study the EDM performance with different electrodes.

Most research in this field has focused on the influence of different electrode materials on EDM performance, and they mainly emphasize MRR, EWR, and surface quality as consideration indicators. However, no extant studies have considered the copying accuracy and recast layer integrity in the EDM of specific microstructures, and none have conducted quantitative evaluations of reduced recast layer thickness.

Xu et al. [21] studied techniques for reducing recast layer and micro-cracks on the surface of 304 stainless steel workpieces machined by reversed polarity micro-EDM. Prior experimental results showed that the machining effect is the best when the pulse width is 0.5 μs, pulse interval is 15 μs, and voltage is 110 V. They also used PMEDM with B_4C powder to modify the surface of Ti-6Al-4V alloy workpieces (the electrical parameters included a voltage of 130 V, a pulse width of 1 μs, and a pulse interval of 10 μs). With the shaking of the tool electrode, micro-grooves (Ra = 0.205 μm) were machined with high shape precision, and noticeably reduced thickness of recast layer. The electrode used in the above experiments was of red copper. On this basis, in this paper, brass, copper-tungsten, and tungsten electrodes were used to carry out EDM on separate Ti-6Al-4V alloy and 304 stainless steel workpiece to study the influence of different electrode materials on recast layer integrity of the machined microstructures, and an effective quantitative analysis of the experimental results was conducted.

2. Experimental Materials And Equipment

V-groove array structures were cut on red copper, brass, copper-tungsten, and tungsten electrode via LSWEDM (AP250LS, Sodick Company, Japan). The physical properties of electrode materials are shown in Table 1 below. The workpiece materials were of 304 stainless steel and Ti-6Al-4V (α + β type) alloy, their main properties are shown in Table 2 The pulse power supply was developed by the research group and the maximum pulse frequency was 5 MHz (Fig. 2a). The insulating medium was a suspension of spark oil and B_4C with 3000 mesh, and the concentration of B_4C powder in the working solution was 6 g/L. After machining, the roughness and microstructure profile of the workpiece surface were measured via laser confocal microscope (VK-X250K, Keyence Company, Japan). The surface morphology of workpieces and the integrity of recast layer were observed using a SEM (Quanta FEG 450, FEI Company, USA).

Table 1
The main physical properties of electrode materials

Electrode Material	Chemical Composition	Density (g/cm^3)	Melting Point(℃)	Resistivity (Ω•m)	Thermal Conductivity (W/m•K)
red copper	Cu:99.9%	8.96	1084	1.72×10^{-8}	401
brass	Cu,Zn:30%	8.73	885	9.00×10^{-8}	88.3
copper-tungsten	Cu:20%,W:80%	14.5	3000	5.15×10^{-8}	238
tungsten	W:99.9%	19.35	3410	5.48×10^{-8}	174

Table 2
The main properties of the workpiece material

Workpiece	Density (g/cm^3)	Melting pint (℃)	Thermal Conductivity (W/m•K)	Electrical Resistivity (Ω•cm)
Ti-6Al-4V alloy	4.43	1660	9.1	17.8×10^{-5}
304 Stainless steel	7.93	1450	16.2	7.2×10^{-5}

3. Microstructure Copying Accuracy

In EDM, the physical characteristics of the electrode and workpiece material have an important influence on material removal amount per discharge. Generally speaking, the higher the corrosion resistance of tool electrode, the smaller TEW and the higher copying accuracy.

Microstructures with high aspect ratio have a wide range of application scenarios, and usually they are more difficult to machine. In order to obtain microstructures with high aspect ratio and high copying accuracy, while considering the uncertainty of machining process and TEW, it is necessary to design microstructures with different sizes to verify their feasibility. In this experiment, microstructure maintained a height of 550 μm, design widths of electrodes used to perform EDM were 150 μm, 250 μm, 350 μm, 450 μm, 550 μm, 650 μm, 750 μm, and 850 μm, and then TEW and reproduction rate were calculated. The results are shown in Fig. 3 below.

According to the processing results, with the decrease of aspect ratio, the reproduction rate first gradually increased and then tended to stabilize (Fig. 3a), while the TEW gradually decreased (Fig. 3b). Because when machining microstructures with a large aspect ratio, the narrow gap fluid resistance between electrode and workpiece was large, making it difficult to discharge bubbles and chips from the machining, and anomalous discharge could easily occur, resulting in low microstructure copying accuracy and large TEW. When aspect ratio was 3.7, the reproduction rate was only 43.8%, and the TEW reached 238 μm. Aspect ratio of 0.85 was the turning point of the polyline, at this time, the reproduction rate was 73.5% and the TEW was 118 μm. If aspect ratio continued to decrease, the reproduction rate and TEW would both undergo little change.

After several experiments were carried out, the V-groove array structure shown in Fig. 4a below was finally machined on electrode. The transverse spacing of microstructures on electrode was 650 μm, the longitudinal height was 550 μm. Using this electrode, PMEDM was conducted on Ti-6Al-4V alloy under voltage of 130 V, pulse width of 1 μs, and pulse interval of 10 μs. The microstructure profile is shown in Fig. 4b, with transverse spacing of 608 μm, and longitudinal height of 432 μm. The results showed that the reproduction rate of microstructure was about 73.5%, and the length of microstructure was reduced by 42 μm and its height was reduced by 118 μm. The size reduction in height was about 3 times that in length, which was due to the small contact area at the tip of microstructure, resulting in accumulated energy and greater TEW. Therefore, only the vertical direction is considered for the TEW referred to in the following section.

4. Results And Discussion

4.1 Microstructure morphology on Ti-6Al-4V alloy machined via PMEDM

Keeping other parameters unchanged, PMEDM was carried out on Ti-6Al-4V alloy using copper, brass, copper-tungsten, and tungsten electrode, and the obtained microstructure morphologies are shown in Fig. 5. The machining conditions are shown in Table 3.

Table 3
Experimental conditions for processing Ti-6Al-4V alloy in PMEDM

Processing Conditions	Description
tool electrode (-)	red copper, brass, copper-tungsten, and tungsten
workpiece (+)	Ti-6Al-4V alloy
voltage	130 V
pulse width	1 μs
pulse interval	10 μs
dielectric fluid	EDM oil mixed with B_4C powders at concentration of 6 g/L

Figure 5 above shows the microstructure morphology of Ti-6Al-4V alloy machined using different electrodes. It can be seen that the workpieces all possessed microstructures high good copying accuracy. The reproduction rates of microstructures machined with four electrodes were 73.5%, 66.9%, 75.2% and

62.3% respectively (Fig. 5d). Among them, the surface roughness of workpiece machined with tungsten electrode was the largest (*Ra =* 0.401 μm), followed by brass electrode (*Ra =* 0. 383 μm), and copper-tungsten electrode (*Ra =* 0. 203 μm), which was similar to the surface quality of workpiece machined with copper electrode (*Ra =* 0. 205 μm). Compared with brass and tungsten electrode, the microstructures processed with copper-tungsten electrode has higher shape precision and higher surface quality (Fig. 5b). That is because copper-tungsten electrode combines the good properties of tungsten and copper, featuring high temperature resistance, high strength, arc erosion resistance, good electric conductivity, heat conductivity and fast heat dissipation, which ensures the stability of machining process.

4.2 Machining performance of Ti-6Al-4V alloy via PMEDM

Figure 6 shows the contour of the electrode after processing. It can be seen that the TEW of brass electrode (Fig. 6a) is larger than that of copper-tungsten and tungsten electrode. The tungsten electrode (Fig. 6c) has high surface finish and experienced less thermal damage after EDM. That is because tungsten has good arcing performance and high arc column stability, so the tungsten electrode is more resistant to arc erosion. There was obvious electrode erosion present on the micro-grooves of brass and copper-tungsten electrode, which may have been caused by the concentration of discharge energy in this area. It was also observed that electrode wear was inversely proportional to the melting point of electrode material, and materials with good tool wear characteristics generally have high melting points and high wear resistance.

Melting and vaporization lead to the removal of material molecules from the workpiece in EDM, and machining performance is greatly affected by the physical properties of electrode materials. Figure 7 above shows the machining performance of Ti-6Al-4V alloy machined with different electrodes in terms of TEW and MRR. As can be seen from the figure, the TEW of copper electrode was the smallest (129 μm), the TEW of brass electrode was the largest (181 μm), while copper-tungsten and tungsten electrode had similar TEW. In terms of MRR, copper electrode had the smallest MRR, which was 218.72 mm^3/min, and copper-tungsten electrode had the highest MRR, reaching 255.39 mm^3/min, which was 16.8% higher than that of copper electrode.

The analysis shows that copper electrode has a high thermal conductivity (401 W/m•K) and temperature transfer coefficient. This high thermal conductivity makes it difficult to accumulate heat in machining process and produce thermal damage, reducing the TEW. At the same time, the rapid loss of energy shortens the duration of spark discharge, and reduces the energy transferred to workpiece. Copper-tungsten and tungsten electrodes have high melting points, high erosion resistance, so it has low TEW, and high machining speed. Generally speaking, copper, copper-tungsten and tungsten electrodes have smaller TEW, while brass electrodes have higher TEW. Compared with copper and brass electrodes, copper-tungsten and tungsten electrodes can achieve higher MRR.

4.3 Recast layer integrity of Ti-6Al-4V alloy machined via PMEDM

The process of discharge erosion is very complex, and is not only manifested in the influence of thermal physical constants of material on its corrosion resistance, but also in the interaction between electrode and workpiece on the energy distribution and transfer, the dispersal and re-solidification of electrical erosion products, etc. Therefore, the use of different materials not only affects TEW and MRR, but also affects the distribution of recast layer and micro-cracks. From Fig. 7 above, the recast layer on microstructure surface machined with brass electrode was 7.21 μm at its thickest, and the recast layer contains thin micro-cracks. The maximum thickness of recast layer on microstructure surface machined using copper-tungsten electrode was 3.35 μm, and recast layer contained microporous. The maximum thickness of recast layer on microstructure surface machined using tungsten electrode was 10.78 μm, and its recast layer also contained obvious micro-cracks. The recast layer was the main host of the micro-cracks, and its thickness affects the intensity, density, and distribution of micro-cracks. Therefore, the effective thinning of the thickness of recast layer has a positive effect on the suppression of the micro-crack phenomenon, and can also greatly improve the surface quality. .

To sum up, in order to obtain microstructures with a high copying accuracy and thin recast layer when machining Ti-6Al-4V alloy via PMEDM, it is recommended to use copper-tungsten electrode, which have a smaller TEW (139 μm) and the greatest MRR (255.39 mm^3/min). This is followed by copper electrode, which feature good machining performance and machinability.

4.4 Recast layer integrity of machined 304 stainless steel

The machining conditions for 304 stainless steel under normal polarity are shown in Table 4, and the machined surface morphologies are shown in Fig. 9 below.

Table 4
Experimental conditions for processing 304 stainless steel in EDM.

Processing Parameters	Description
electrode (-)	brass, copper-tungsten, tungsten
workpiece (+)	304 stainless steel
dielectric fluid	EDM oil
voltage	250 V
pulse interval	5 μs
pulse width	7 μs

Figure 9 below shows the surface morphology of 304 stainless steel workpieces machined at normal polarity using different electrodes. It can be seen that the surface quality of the workpiece machined by this method is not ideal, and the surface contains many discharge pits, accompanied by surface erosion. Due to residual stress during the discharge process, cracks were produced on the surface. Measurement showed that their *Ra* values were above 0.8 μm.

In order to improve the surface quality, continue to finish machining the workpiece through the negative polarity by micro-EDM. The electrical parameters used in this process included a pulse width of 0.5 μs, a pulse interval of 15 μs, a voltage of 110 V, and a machining depth of 50 μm. The obtained results are shown in Fig. 10 below. The processing environment is as shown in Table 5.

Table 5
Experimental conditions for processing 304 stainless steel in micro-EDM

Processing arameters	Description
polarity	workpiece negative polarity
voltage	110 V
pulse interval	0.5 μs
pulse width	15 μs

As can be seen from Fig. 10 above, the machined surface of brass electrode (Fig. 10a) contains slender cracks, a surface roughness (*Ra*) of 0. 58 μm, and a recast layer of 11.16 μm at its thickest point (Fig. 10b). That is because brass has low thermal conductivity, and drastic temperature changes deform the material and generate thermal stress, thus producing micro-cracks. The diameter and density of discharge pits on the machined surface of copper-tungsten electrode (Fig. 10c) are highly noticeable; the surface roughness (*Ra*) is 0. 62 μm, the recast layer is 6.97 μm at its thickest point, and it contains obvious micro-cracks and micro-pores. Compared with brass and copper-tungsten electrodes, the machined surface of tungsten electrode (Fig. 10e) is smooth, with almost no erosion visible, which indicates that there was little destructive arc discharge during its machining performance. Measurement shows that its surface roughness (*Ra*) was 0. 35 μm, and its recast layer was 3.65 μm at its thickest point.

To sum up the results, when machining 304 stainless steel with positive polarity micro-EDM, the surface quality of the workpiece is poor and it is difficult to meet the use requirements. So it is recommended to use reversed polarity micro-EDM for machining, which can effectively improve surface quality, and the use of copper electrode and tungsten electrode can reduce surface micro-cracks and the thickness of recast layer.

5. Conclusions

During the fabrication of microstructures produced through the utilization of micro-EDM, the thermal and physical characteristics of both workpieces and electrode materials at room and high temperatures have considerable influence on the material removal per discharge, the quality surface, and the distribution of recast layer. Materials with good tool wear characteristics generally have high melting points and wear resistance, so improved MRR, reduced TEW, thinner recast layers, and finer surface quality can be obtained by using suitable electrode materials. In view of the experimental results, the following conclusions can be drawn:

(1) Considering the uncertainty of both the machining process and the TEW, a designed microstructure with a height of 550 μm and a width of 650 μm boasts higher degrees of copying accuracy. Under these conditions, its reproduction rate will be 73.5%, and its TEW is 118 μm. If the aspect ratio continues to decrease, the reproduction rate and TEW will not change rather little.

(2) Copper-tungsten electrodes are recommended for use in PMEDM of Ti-6Al-4V alloy as they possess a smaller TEW (139 μm), the highest MRR (255.39 mm^3/min) and a thinner recast layer (3.35 μm). The secondary preference is for copper electrodes, which feature strong machining performance and high machinability.

(3) When machining a 304 stainless steel workpiece with reversed polarity, and taking both the surface quality and recast layer thickness into full account, the use of copper electrodes and tungsten electrodes will produce reduced TEW, and the thickness of the recast layer on the workpiece surface can be effectively reduced to about 3 μm.

Declarations

Ethical Approval & Consent to Participate

The article follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects.

Consent to Publish

All authors have read and agreed to publish the manuscript.

Competing Interests

The authors declare no conflicts of interest.

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Authors Contributions

Bin Xu, Sheng-gui Chen, Man-qun Lian designed all experiments included in this study, wrote and modified this manuscript. Xiao-yu Wu and Feng Luo assisted in conducting the experiments. Jian-guo Lei, Hang Zhao, Tai-jiang Peng and Jun Yang made suggestions about this manuscript.

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Figures

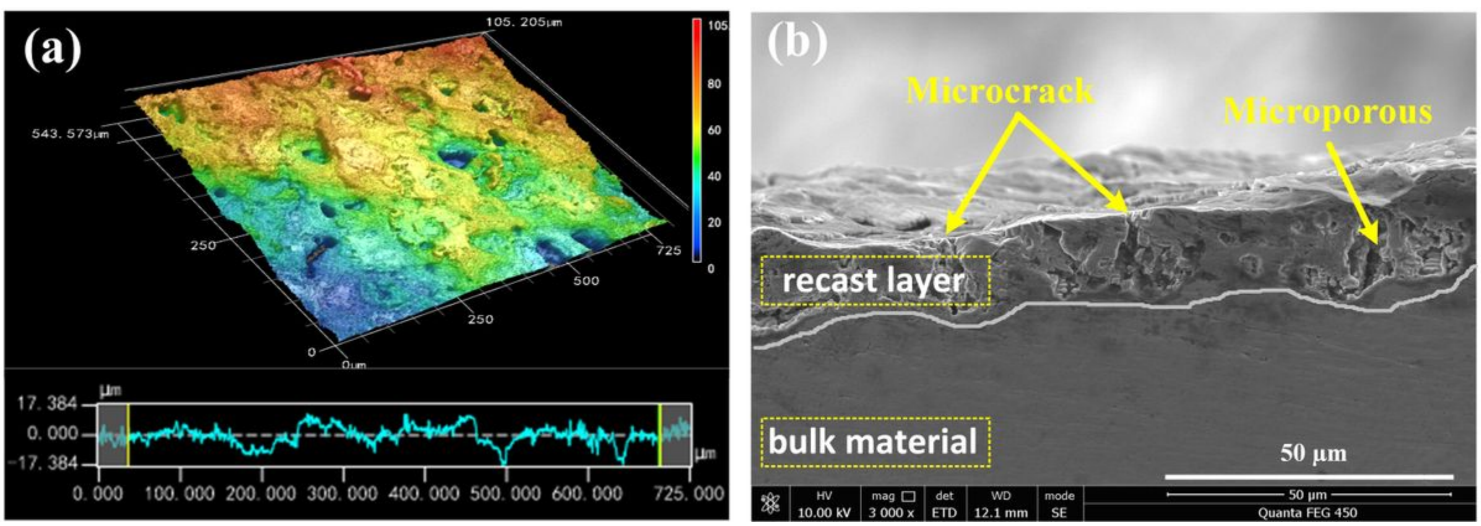

Figure 1

Characteristics of titanium alloy machining in EDM: (a) 3D laser surface topography, (b) recast layer on section

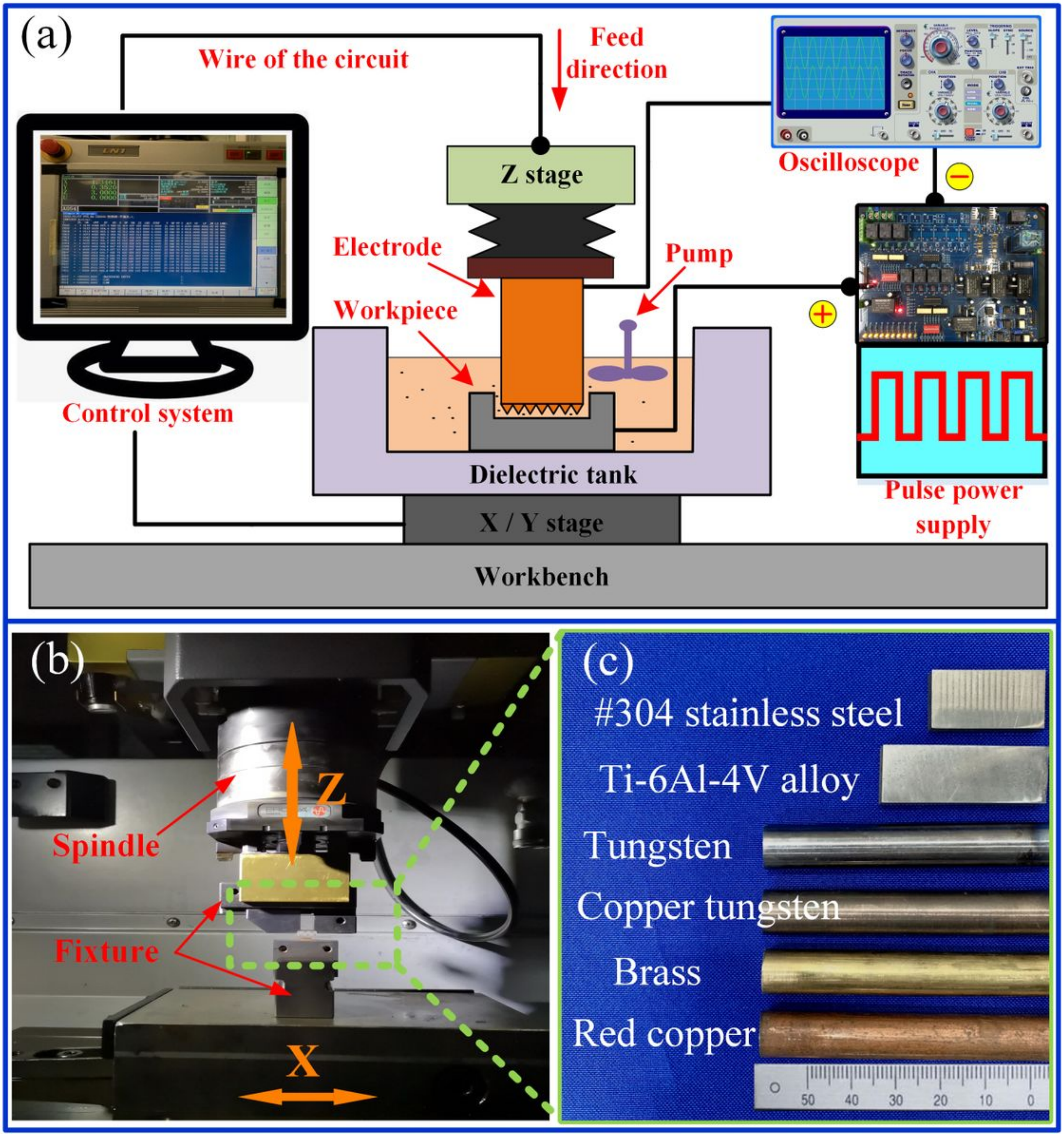

Figure 2

Experimental equipment and materials in this paper

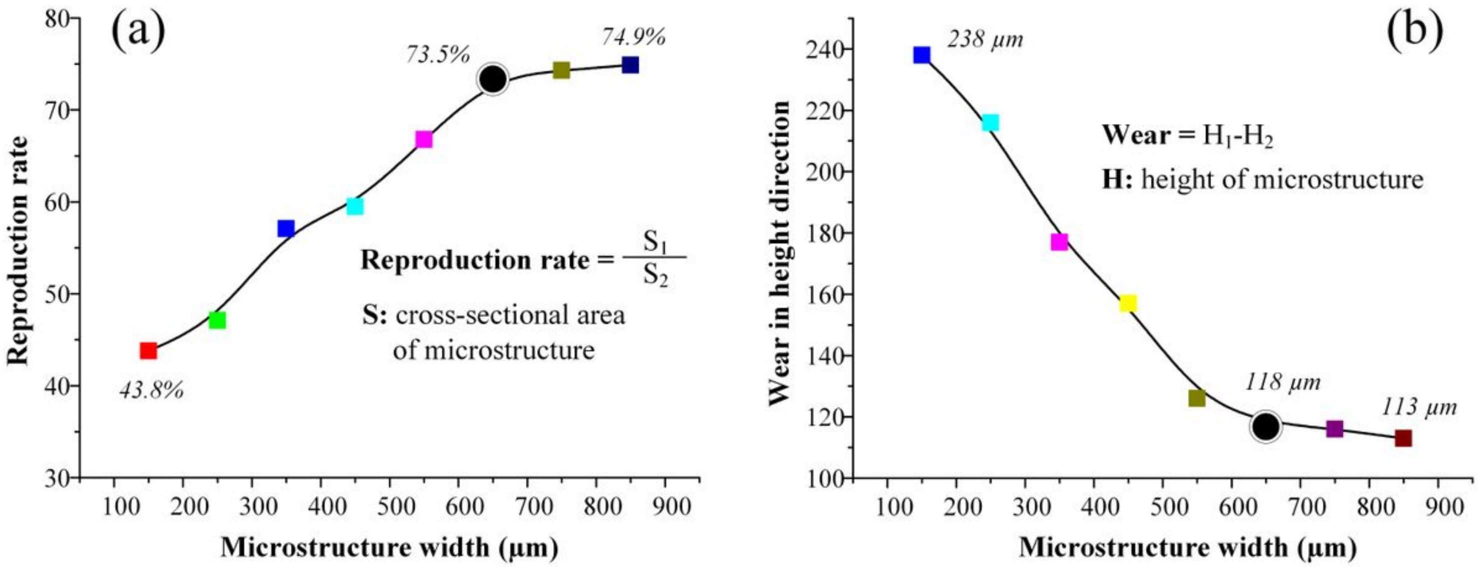

Figure 3

Processing results of microstructures with different widths: (a) reproduction rate, (b) wear in height direction

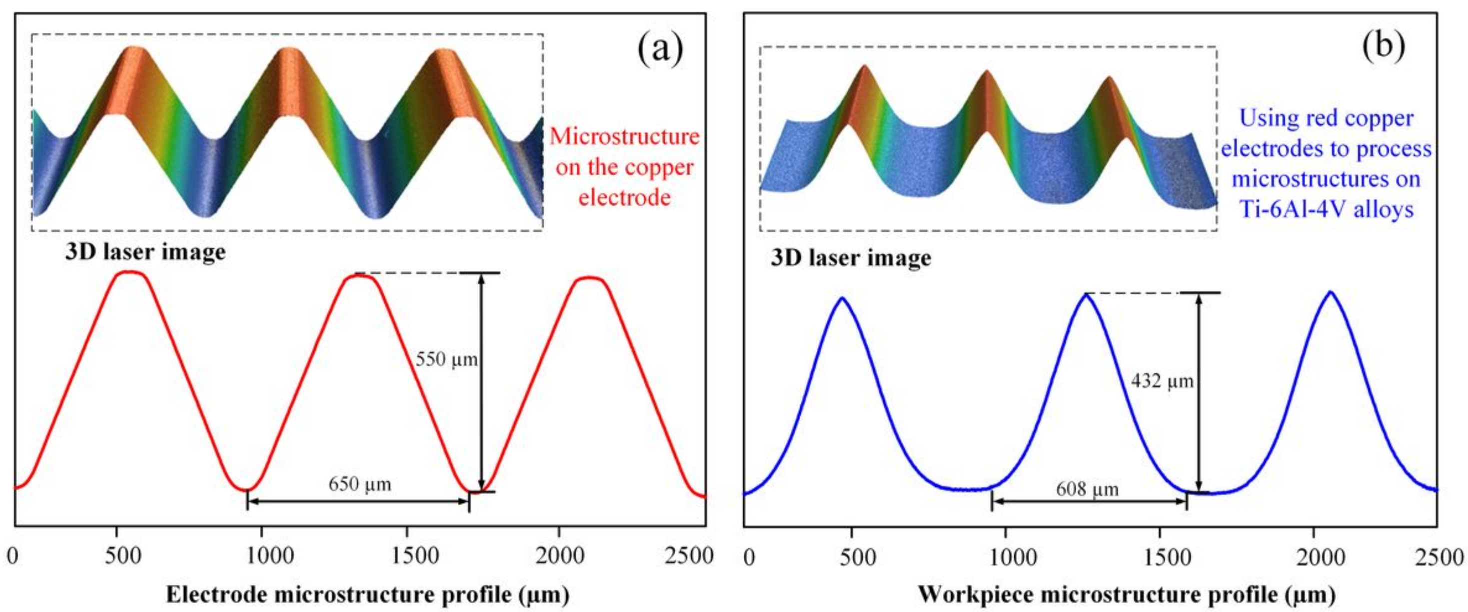

Figure 4

Microstructure profile and 3D laser map: (a) electrode, (b) workpiece

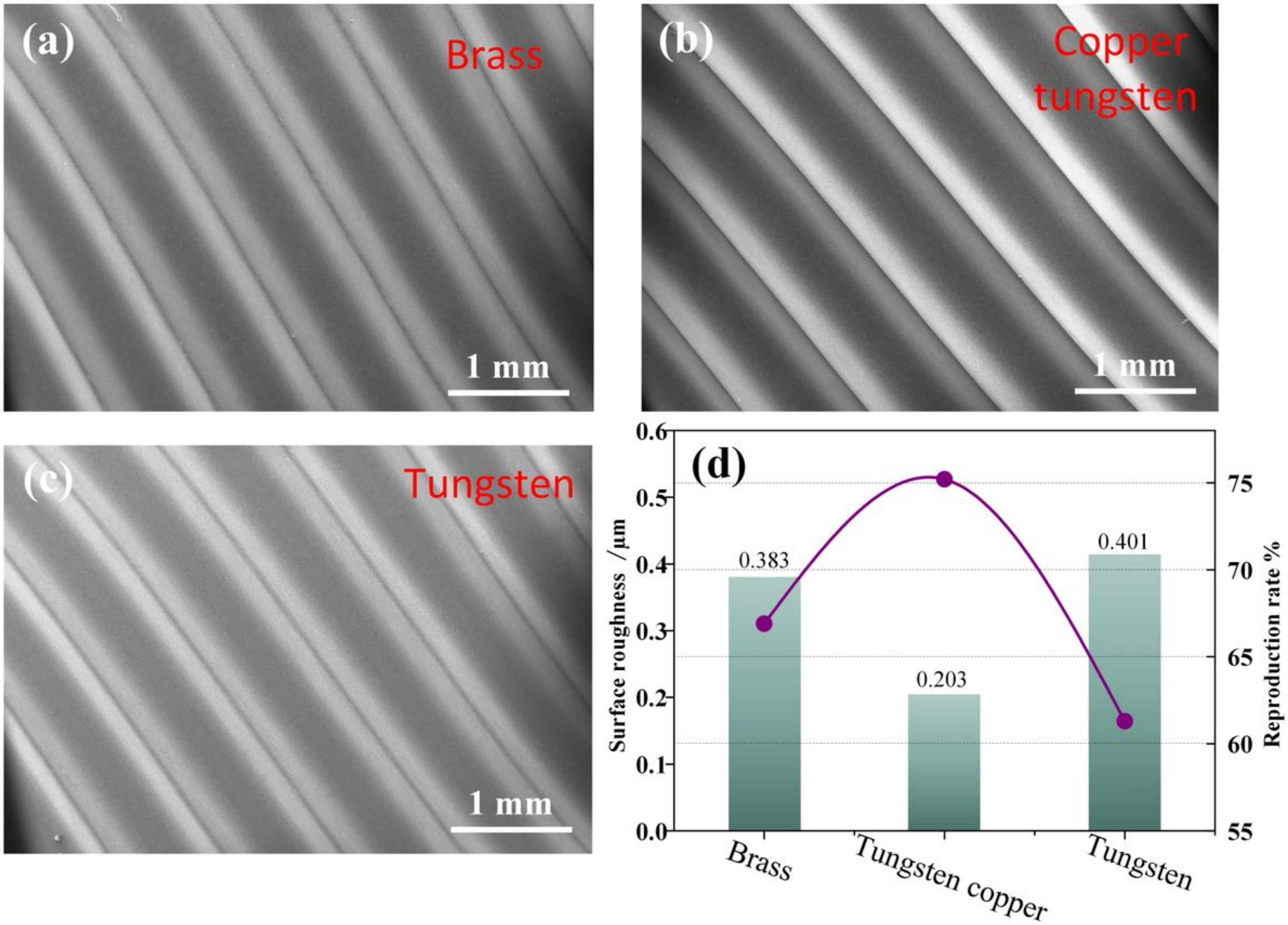

Figure 5

Microstructure morphology of Ti-6Al-4V alloy processed by different electrodes: (a) brass, (b) copper-tungsten, (c) tungsten, (d) surface roughness

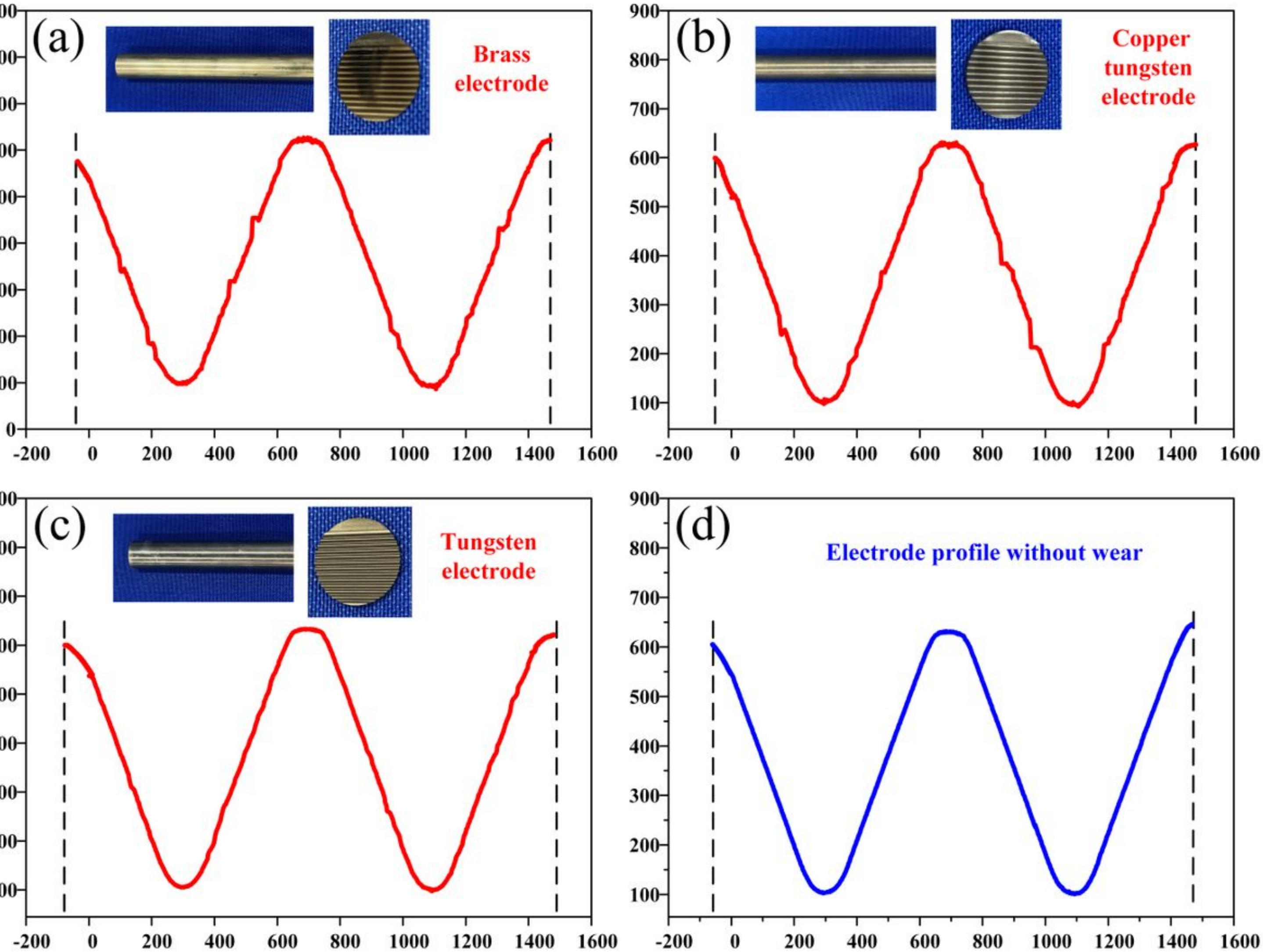

Figure 6

The wear diagram of different electrodes: (a) brass electrode, (b) copper-tungsten electrode, (c) tungsten electrode, (d) electrode without wear

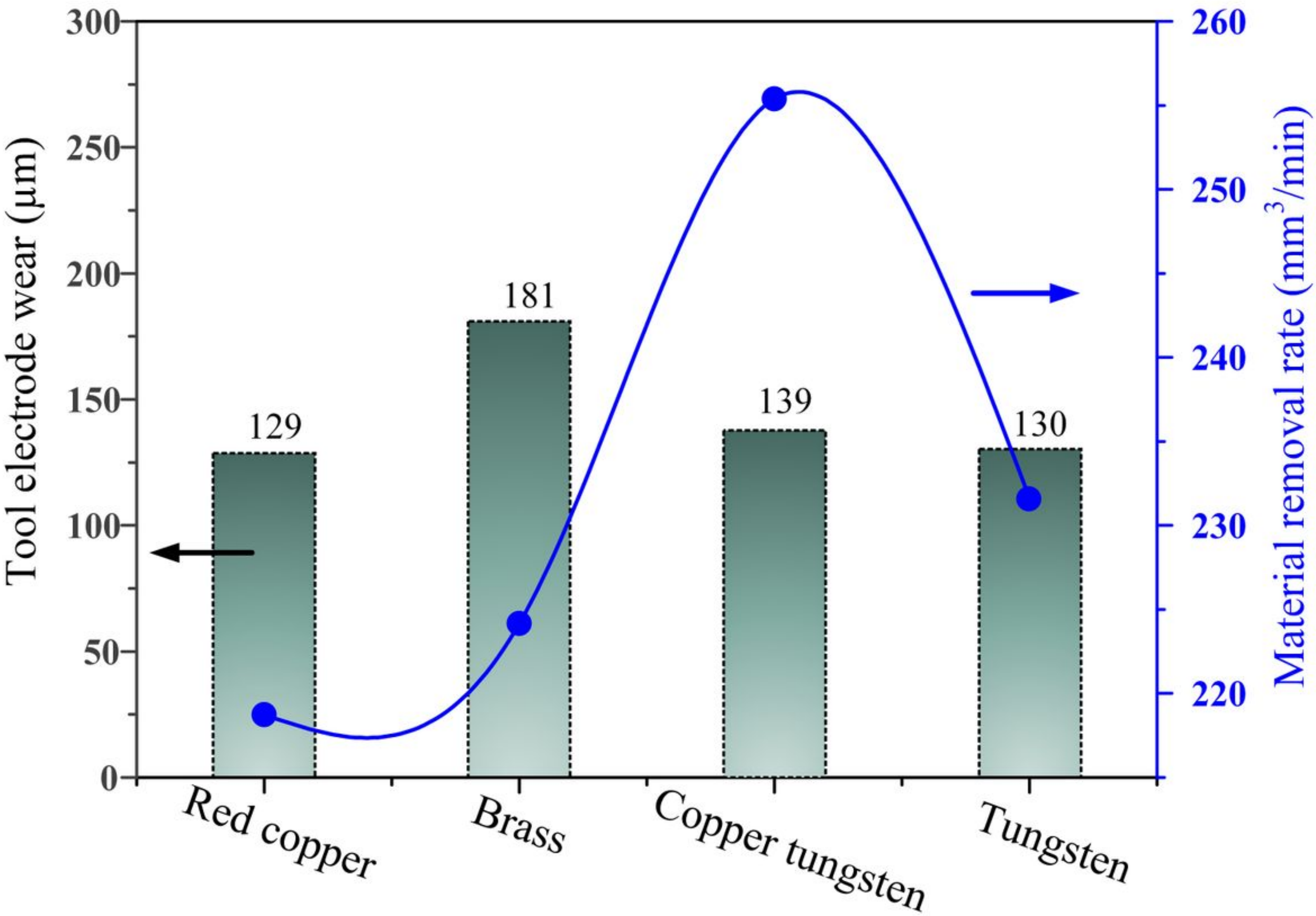

Figure 7

Tool electrode wear and material removal rate

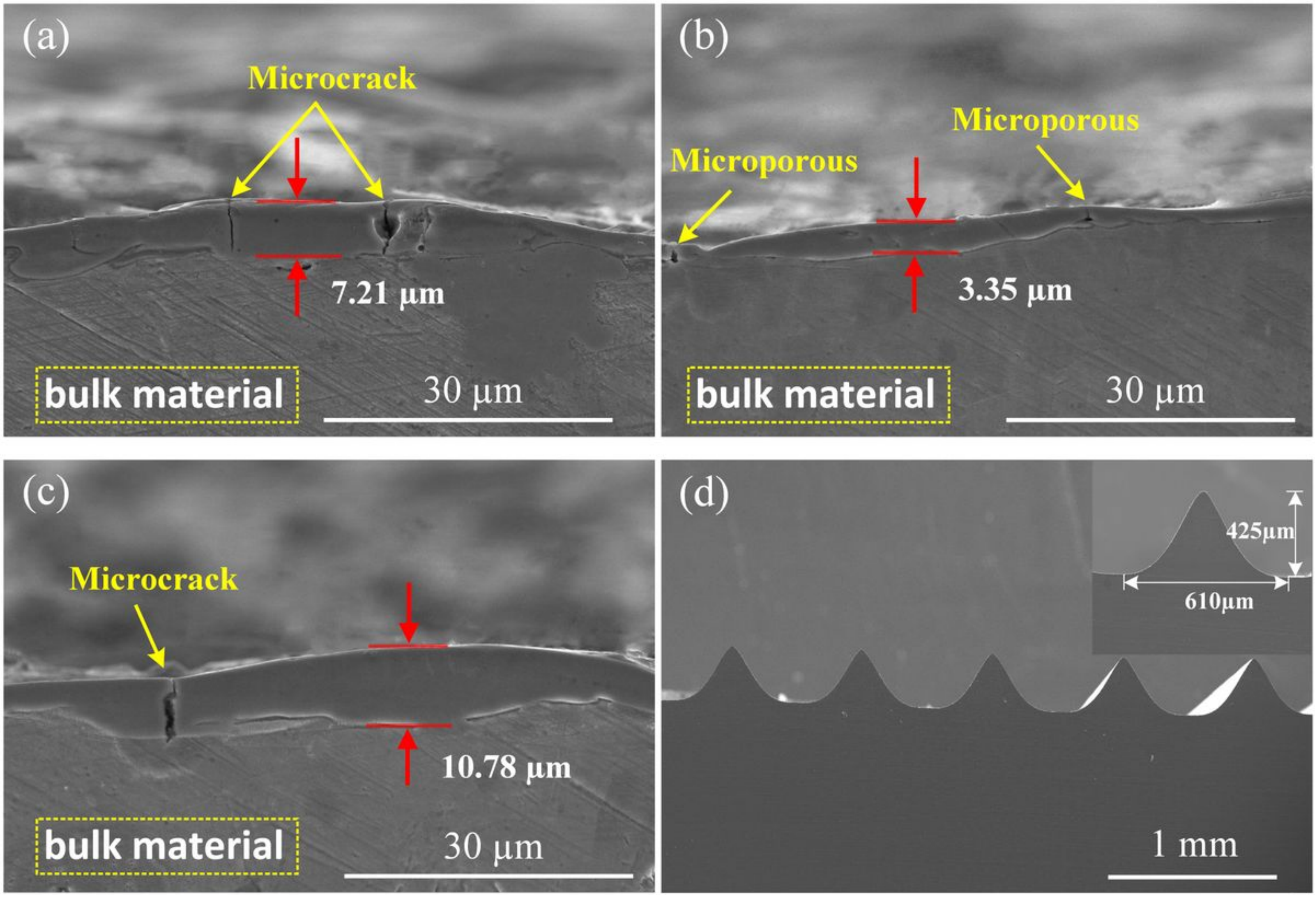

Figure 8

Distribution of recast layers of Ti-6Al-4V alloy processed by different electrodes: (a) brass, (b) copper-tungsten, (c) tungsten, (d) microstructure profile

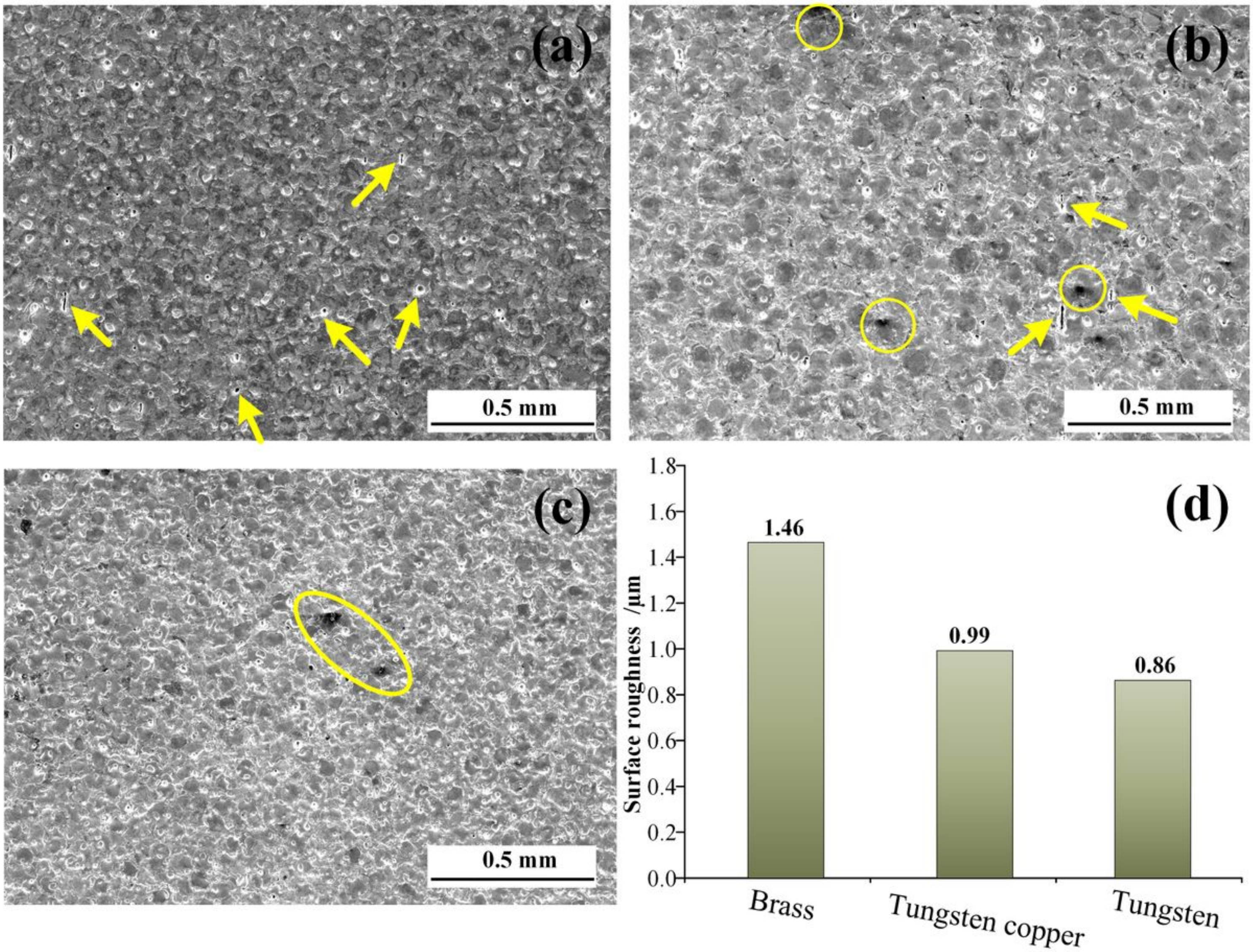

Figure 9

Surface morphology of 304 stainless steel machined in normal polarity

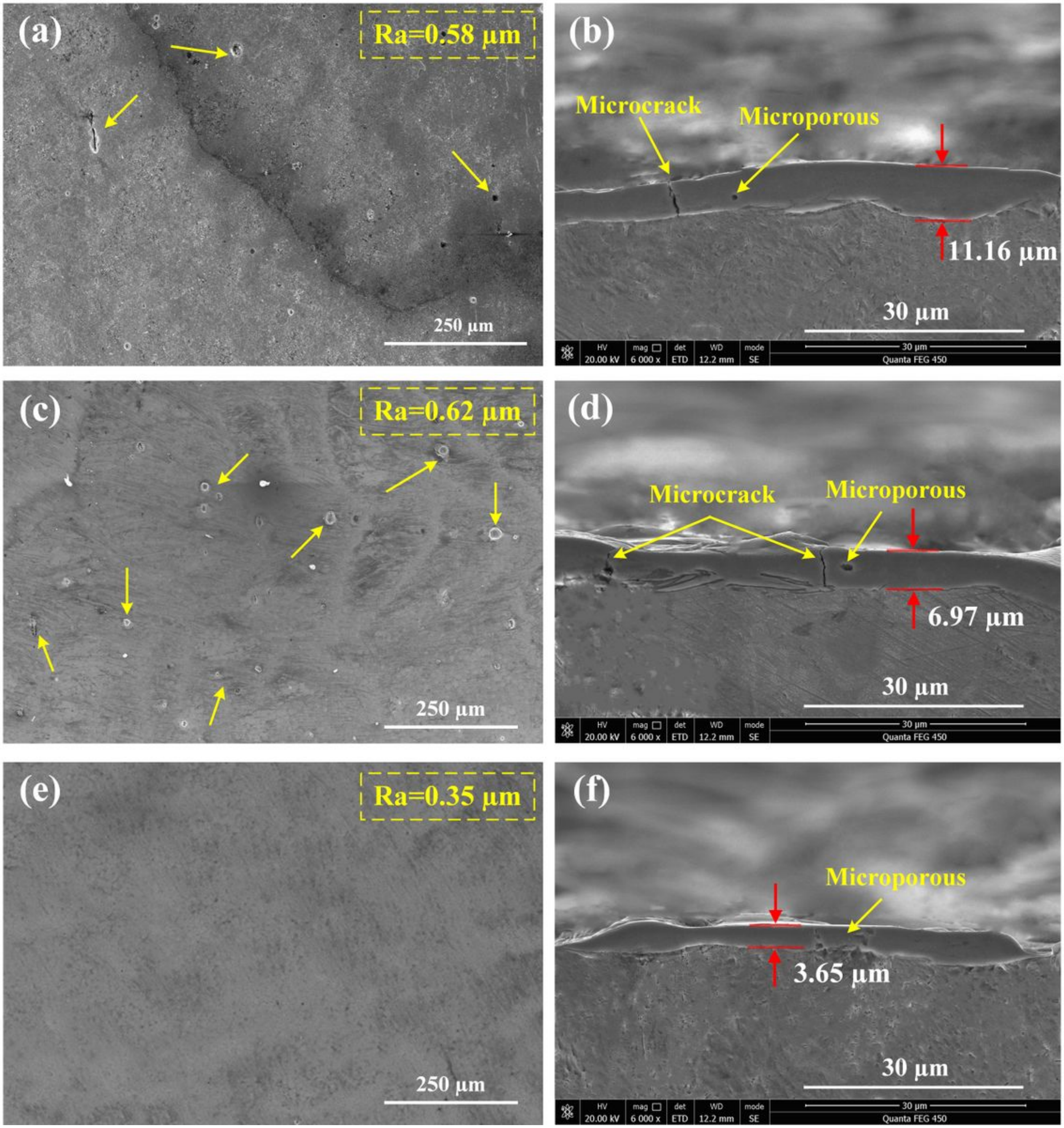

Figure 10

Surface morphology and thickness of recast layer: (a)(b) brass electrode, (c)(d) copper-tungsten electrode, (e)(f) tungsten electrode