Study on the micro-EDM processing characteristics of Ti-6Al-4V alloy with different electrode materials

Sheng-gui Chen¹ · Man-qun Lian¹ · Xiao-yu Wu¹ · Jian-guo Lei¹ · Hang Zhao¹ · Tai-jiang Peng¹ · Feng Luo¹ · Jun Yang² · Bin Xu¹

Received: 25 March 2021 / Accepted: 7 July 2021 / Published online: 20 July 2021 © The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2021

Abstract

Ti-6Al-4V alloy has been widely used in industrial fields. Electrical discharge machining (EDM) is a commonly used technology for machining Ti-6Al-4V alloy. During EDM of Ti-6Al-4V alloy, the thermal and physical characteristics of tool electrode have an important influence on processing characteristics. In order to study the influence of different electrode materials on the processing characteristics of Ti-6Al-4V alloy, brass electrode, copper tungsten electrode, and tungsten electrode were used to perform EDM of Ti-6Al-4V alloy. In this paper, electrodes with V-groove array structures were designed to carry out powder mixed electrical discharge machining (PMEDM) of Ti-6Al-4V alloy, and the machining results were evaluated based on four indicators: microstructures morphology, tool electrode wear (TEW), material removal rate (MRR), and recast layer thickness (RLT). The processing results show that copper tungsten electrode is recommended to machine Ti-6Al-4V alloy because it has the highest reproduction rate (75.2%), a smaller TEW (139 μm), the highest MRR (255.39 mm³/min), and a thinner RLT (3.35 μm).

Keywords PMEDM · Microstructure · Recast layer · Processing characteristics

1 Introduction

Ti-6Al-4V alloy has good heat resistance, strength, plasticity, toughness, and corrosion resistance. The industrial application of Ti-6Al-4V alloy has accounted for 75~85% of all titanium alloys. Electrical discharge machining (EDM) is a commonly used technology for machining Ti-6Al-4V alloy [1–3].

Different material electrodes exhibit various wear rates in EDM. To make full use of such characteristic, Lei et al. [4] used copper, silicon and copper-silicon alloy disc foils to construct a laminated disc electrode and then applied it in EDM to process microgroove on the titanium alloy workpieces. To obtain fine surface finish from micro-EDM, Jahan et al. [5] made electrodes from tungsten, copper tungsten, and silver tungsten and found that silver tungsten electrodes appeared to be the best choice to perform die-sinking micro-EDM. Lee and Li [6] used copper tungsten electrode, graphite electrode, and copper electrode to perform EDM of tungsten carbide, which found that copper tungsten electrode was the most suitable for process tungsten carbide. Hascalik and Caydas [7] used graphite electrode, electrolytic copper electrode, and aluminum electrode to carry out EDM of Ti-6Al-4V. The experimental results showed that the surface recast layer processed by the copper electrode contained obvious micro-cracks. In EDM, Boujelbene et al. [8] analyzed the effect of machining parameters on the surface characteristics of X200Cr15 and 50CrV4 by using copper electrode and graphite electrode. By using copper tungsten electrode, copper electrode, and graphite electrode, Khan et al. [9] studied the influence of electrode material on the surface characteristics of EDM machined Ti-5Al-2.5Sn. They also used these three types of electrodes to process Ti-5Al-2.5Sn titanium alloy with reverse polarity, and the experimental results showed that the copper electrode produced the lowest Ra [10]. Choudhary et al. [11] performed a new model EDM for processing stainless steel 316 by using copper electrode, brass electrode, and graphite electrode, which found that copper electrode had higher material removal rate (MRR).

Using brass electrode and copper electrode in EDM of 45-carbon steel and W18Cr4V, Xue et al. [12] found that brass...
electrode were able to achieve higher MRR. Bhaumik and Maity [13] used copper electrode, brass electrode, and zinc electrode to carry out EDM of Ti-5Al-2.5Sn titanium alloy. From the machining results, it was found that thinner and more uniform recast layer was generated on the machined surface by using copper electrode. Carlini et al. [14] researched the influence of two different types of copper tungsten (CuW) electrode to conduct EDM of cemented tungsten carbide. Based on the processing results, it found that the CuW85 electrode presented lower TEW and higher MRR than that of CuW65 electrode. Selvarajan et al. [15] did micro-EDM of SS316 steel by using copper electrode and graphite electrode, which showed that graphite electrode performed better processing quality. By adopting copper electrode, brass electrode, and stainless steel electrode in EDM, Raza et al. [16] studied the influence of three input parameters on the MRR, surface roughness, and electrode wear rate (EWR). 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. By combining micro-EDM with negative polarity micro-EDM, Xu et al. [17] reduced the recast layer and micro-cracks on the surface of 304 stainless steels.

Micro-EDM is one of the most common processes for machining Ti-6Al-4V alloy. However, the surface machined by micro-EDM inevitably features recast layer and micro-cracks. These disadvantages have adverse impact on the surface quality (Fig.1a) and performance of the components, which may cause the parts to fail [18, 19]. As shown in the Fig.1, the surface of the Ti-6Al-4V alloy machined by EDM has obvious recast layer (with thickness ranges from 23.4 to 36.1 μm), micro-cracks, and microporous (Fig.1b).

In order to investigate the influence of different electrode materials on the processing characteristics of Ti-6Al-4V alloy, this paper used brass electrode, copper tungsten electrode, and tungsten electrode to perform powder mixed electrical discharge machining (PMEDM) of Ti-6Al-4V alloy. The paper studied the influence of electrode material on tool electrode wear (TEW), material removal rate (MRR), and the recast layer thickness on the Ti-6Al-4V alloy.

2 Experimental materials and equipment

Functional-surface microstructures possess the advantages of improved lubrication conditions, reduced friction, and enhanced heat dissipation performance. In this paper, V-groove array structures were cut on the surface of brass electrode, copper tungsten electrode, and tungsten electrode via LSWEDM (AP250LS, Sodick Company, Japan). The physical properties of electrode materials are shown in Table 1. The workpiece material was Ti-6Al-4V (α+β type) alloy, and its 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 dielectric fluid was spark oil with 3000 mesh B4C suspensions, and the concentration of B4C powder in spark oil was 6 g/L. During the processing, the pump had been stirring continuously at a constant speed to ensure that processing debris would not be deposited on the gaps. After machining, the surface 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 scanning electron microscope (Quanta FEG 450, FEI Company, USA).

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 microstructure used to perform EDM were 150 μm, 250 μm, 350 μm, 450 μm, 550 μm, 650 μm, 750 μm, and 850 μm. TEW and reproduction rate were calculated. The results are shown in Fig. 3.

The contour of the microstructure was accurately measured by laser confocal microscope (VK-X250K, Keyence Company, Japan) and the cross-sectional area was calculated by software (VK-X Series, Keyence Company, Japan). In order to obtain accurate calculation results, the contour of the microstructure was measured 5 times, and then the average value of cross-sectional area can be calculated. As shown in Fig. 3a, with the decrease of aspect ratio, the reproduction rate first gradually increased and then tended to stabilize. As shown in Fig. 3b, with the decrease of aspect ratio, the TEW gradually decreased. 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 gap. Under these circumstances, the anomalous discharge could easily occur, which could result in low microstructure copying accuracy and large TEW. When width of microstructure was 150 μm (with aspect ratio of 3.7), the reproduction rate was only 43.8%, and the TEW reached 238 μm. Width of 650 μm (with 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 was finally machined on electrode. The transverse width of microstructures on electrode was 650 μm, and 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 on the Ti-6Al-4V alloy surface is shown in Fig. 4b, with transverse width of 608 μm and longitudinal height of 432 μm. The reproduction rate of microstructure was about 73.5%. The width 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 width, 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 was 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

Ti-6Al-4V alloy is a typical representative of non-ferrous metals and is widely used in aerospace, medical equipment, and other industries. Keeping other parameters unchanged, PMEDM was carried out on Ti-6Al-4V alloy using brass electrode, copper tungsten electrode, and tungsten electrode. The machining conditions are shown in Table 3, and the obtained microstructure morphologies are shown in Fig. 5.

Figure 5 shows the microstructure morphology of Ti-6Al-4V alloy machined using different electrode material. It can be seen that using this process can better reproduce the microstructure on the electrode to the Ti-6Al-4V alloy workpiece. The reproduction rates of microstructures machined with different electrodes (brass electrode, copper tungsten electrode, and tungsten electrode) were 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).

| Electrode material | Chemical composition | Density (g/cm³) | Melting point(°C) | Resistivity (Ω-m) | Thermal conductivity (W/m·K) |
|--------------------|----------------------|----------------|-----------------|-----------------|-----------------------------|
| 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                         |

| Workpiece          | Density (g/cm³) | Melting point (°C) | Thermal conductivity (W/m·K) | Electrical resistivity (Ω·cm) |
|--------------------|----------------|--------------------|-------------------------------|-------------------------------|
| Ti-6Al-4V alloy    | 4.43           | 1660               | 9.1                           | 17.8×10⁻⁵                    |
Fig. 2 Experimental equipment and materials in this paper

Fig. 3 Processing results of microstructures with different widths: a reproduction rate; b wear in height direction

Fig. 4 Microstructure profile and 3D laser map: a electrode; b workpiece
and copper tungsten electrode (Ra = 0.203 μm). Compared with brass electrode and tungsten electrode, the microstructures processed with copper tungsten electrode have higher shape precision and higher surface quality (Fig. 5b).

Early EDM electrodes used copper or graphite electrodes, which are cheap but not resistant to ablation. Copper tungsten electrode combines the good properties of tungsten electrode and copper electrode, featuring high temperature resistance, high strength, arc erosion resistance, good electric conductivity, and heat conductivity, which ensures the stability of machining process. In order to improve the accuracy of the processed parts and reduce the electrode wear, the tungsten copper material as the electro-processing electrode should have the highest possible density and uniformity of the structure, especially the elongated rod-shaped, tubular, and special-shaped electrodes.

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

| Processing conditions | Description |
|-----------------------|-------------|
| Tool electrode (−)    | 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 B₄C powders at concentration of 6 g/L |

#### 4.2 Wear of the three electrodes

In EDM process, tool wear is one of the primary factors affecting geometrical precision of workpiece. The thermal and mechanical stability at high temperature and the microstructure of the material have an important influence on tool wear.

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 electrode 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, which make the tungsten electrode have more resistant to arc erosion. There was obvious electrode erosion present on the micro-grooves of brass electrode and copper tungsten electrode, which may have been caused by the concentration of discharge energy. It was also observed that electrode wear was inversely proportional to the melting point of electrode material. Electrode material with good tool

![Fig. 5](image-url)
wear characteristics generally have high melting points and high wear resistance.

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

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 shown in Fig. 7, the TEW of tungsten electrode was the smallest (130 μm), and the TEW of brass electrode was the largest (181 μm); between them is copper tungsten electrode (139 μm). In terms of MRR, brass electrode had the smallest MRR (224.41 mm³/min), and copper tungsten electrode had the highest MRR (255.39 mm³/min), followed by tungsten electrode (232.47 mm³/min).
The analysis shows that brass electrode has lowest thermal conductivity (88.3 W/m·K) which causes processing heat concentration and increases wear. Copper tungsten electrode has high thermal conductivity (238 W/m·K) and temperature transfer coefficient. The high thermal conductivity makes it difficult to accumulate heat in machining process, and this helps to reduce 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 electrode and tungsten electrode have high melting points (over 3000 °C) and high erosion resistance. These factors are beneficial to reduce the TEW and improve machining speed. Generally speaking, copper tungsten electrode and tungsten electrode have smaller TEW, while brass electrodes have higher TEW. Compared with brass electrode and tungsten electrode, copper tungsten can achieve higher MRR.

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

Under the effect of heat generated from EDM, there will produce recast layer on the workpiece surface. The influence factors on the recast layer mainly include the material properties of the workpiece, the material properties of electrode, and the parameters of EDM. Electrode plays an important role in EDM, and it has an important influence on the recast layer on the workpiece surface. In order to study the influence of electrode materials on recast layer, tool electrodes of different materials were used to conduct PMEDM of Ti-6Al-4V alloy. Tool electrodes were made of brass, copper tungsten, and tungsten. The parameters of PMEDM are shown in Table 3, and the experimental results are shown in Fig. 8. The thickness of the recast layer marked in Fig. 8 is the thickest position in the measurement area, which is convenient for quantitative comparison and analysis.

Based on the experimental results shown in Fig. 8, the recast layer on microstructure surface machined by brass electrode was 7.21 μm at its thickest position, and the recast layer contains thin micro-cracks. The maximum thickness of recast layer on microstructure surface machined by copper tungsten electrode was 3.35 μm, and recast layer contained microporous. The maximum thickness of recast layer on microstructure surface machined by tungsten electrode was 10.78 μm, and the recast layer also contained obvious micro-cracks. From the experimental results, it can be known that the processing defects such as micro-cracks and microporous were mainly located in the recast layer. And the thinner the recast layer, the fewer these processing defects. Therefore, the thin recast layer has a positive effect on the suppression of the processing defects and can improve the surface quality.

To sum up, in order to obtain microstructures with 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), the greatest MRR (255.39 mm³/min), and a thinner RLT (3.35 μm).

5 Conclusions

In order to research the influence of different electrode materials on the processing characteristics of Ti-6Al-4V alloy, this paper used brass electrode, copper tungsten electrode, and tungsten electrode to perform PMEDM of Ti-6Al-4V alloy. The paper studied the influence of electrode material on the recast layer, TEW, and MRR on the Ti-6Al-4V alloy. 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 V-groove array structure with height of 550 μm and width of 650 μm can achieve higher degrees of copying accuracy. Under these conditions, its reproduction rate can reach 73.5%, and its TEW is 118 μm.

(2) Copper tungsten electrode is recommended for application in the PMEDM of Ti-6Al-4V alloy, which features a smaller TEW (139 μm), the greatest MRR (255.39 mm³/min), and a thinner RLT (3.35 μm).

(3) The processing defects such as micro-cracks and micro-porous were mainly located in the recast layer. The thin recast layer has a positive effect on the suppression of the processing defects and can improve the surface quality. In future, the research will focus on predicting the thickness of recast layer by numerical simulation of the temperature field of EDM, which can guide practical EDM.

Acknowledgements The authors are also grateful to the colleagues for their essential contribution to the work.

Author contributions Bin Xu, Sheng-gui Chen, and 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.

Funding This work is supported by the National Natural Science Foundation of China (Grant Nos. 51775351) and the Science and Technology Planning Project of Shenzhen Municipality (Grant Nos. JSGG20201102145402008). The authors would like to thank the colleagues for their essential contribution to the work.

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and 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 for publication All authors have read and agreed to publish the manuscript.

Competing interests The authors declare no competing interests.

References

1. Xu B, Chen SG, Lei JG, Zhao H, Zhu LK (2020) The wear of 3D microelectrode in micro electrical discharge machining. Int J Adv Manuf Technol 107(1):645–651
2. Xu B, Wu XY, Lei JG, Cheng R, Ruan SC, Wang ZL (2015) Laminated fabrication of 3D micro-electrode based on WEDM and thermal diffusion welding. J Mater Process Technol 221:56–65
3. Qudeiri JA, Mourad A, Ziout A, Abidi MH, Elkaseer A (2018) Electric discharge machining of titanium and its alloys: review. Int J Adv Manuf Technol 96(1):1319–1339
4. Lei JG, Wu XY, Xu B, Zhu LK, Zhou ZW, Guo DJ, Jiang K, Zhao YH (2020) Fabrication of microgrooves by EDM using a laminated disc electrode consisted of different material foils. Procedia CIRP 95:578–583
5. Jahan MP, Wong YS, Rahman M (2009) A study on the fine-finish die-sinking micro-EDM of tungsten carbide using different electrode materials. J Mater Process Technol 209(8):3956–3967
6. Lee SH, Li XP (2001) Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide. J Mater Process Technol 115(3):344–358
7. Hasalik A, Caydas U (2007) Electrical discharge machining of titanium alloy (Ti-6Al-4V). Appl Surf Sci 253(22):9007–9016
8. Boujelbene M, Bayraktar E, TEBNI W, Salem SB (2009) Influence of machining parameters on the surface integrity in electrical discharge machining. Arch Mater Sci Eng 37(2):110–116
9. Khan M, Rahman MM, Kadigama K (2015) An experimental investigation on surface finish in die-sinking EDM of Ti-5Al-2.5Sn. Int J Adv Manuf Technol 77(9-12):1727–1740
10. Khan M, Rahman MM (2017) Surface characteristics of Ti-5Al-2.5Sn in electrical discharge machining using negative polarity of electrode. Int J Adv Manuf Technol 92(1):1–13
11. Choudhary S, Kant K, Saini P (2013) Analysis of MRR and SR with different electrode for SS 316 on die-sinking EDM using Taguchi technique. Glob J Res Eng 13:15–21
12. Xue B, Zhang Q, Zhang J, Kong D, Yang T (2013) Machining efficiency of powder mixed near dry electrical discharge machining based on different material combinations of tool electrode and workpiece electrode. J Manuf Process 15(4):474–482
13. Bhaumik M, Maity K (2018) Effect of electrode materials on different EDM aspects of titanium alloy. Silicon 11(1):187–196
14. Carlini GC, Amorim FL, Weingaertner WL (2019) Influence of different grades of CuW electrodes when die sinking EDM of cemented carbide. Int J Adv Manuf Technol 104(1-4):1065–1074
15. Selvarajan L, Rajavel R, Venkataramanan K, Elango T, Dhinagaran M (2020) An experimental investigations and optimization of performance measures in EDM using copper and graphite electrodes. Mater Today Proc. https://doi.org/10.1016/j.matpr.2020.02.816
16. Raza MH, Wasim A, Ali MA, Hussain S, Jahanzaib M (2018) Investigating the effects of different electrodes on AL6061-SiC-7.5 wt% during electric discharge machining. Int J Adv Manuf Technol 99(9):3017–3034
17. Xu B, Chen SG, Liang X, Lei JG, Shi HY, Fu LY, Yang J, Peng TJ, Zhao H, Zhu LK (2020) Recast layer removal of 304 stainless steel by combining micro-EDM with negative polarity micro-EDM. Int J Adv Manuf Technol 107(11):4713–4723
18. Mu X, Zhou M, Ye Q (2019) Improving surface integrity and surface roughness by forming multi-discharging channels from one pulse in EDM. Int J Adv Manuf Technol 102(9):3181–3195
19. Wu XL, Liu YH, Zhang XX, Dong H, Zheng C, Zhang F, Sun Q, Jin H, Ji RJ (2020) Sustainable and high-efficiency green electrical discharge machining milling method. J Clean Prod 274:123040

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.