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Study of Cutting Force and Tool Wear in High Frequency Electrical Discharge Assisted Milling Using Flexible Electrode

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Previous research has validated the machinability of the new machining method for electrical discharge assisted milling (EDAM). However, due to the shortcomings of the EDAM tool, such as the inability to compensate the electrode and the small discharge area, its further popularization and application are seriously limited. This paper introduces a high frequency EDAM (HF-EDAM) process based on a novel tool with flexible electrodes. In this study, the material removal mechanism of HF-EDAM technology under different machining parameters is deeply explored. By analyzing the cutting force and tool wear after machining, the specific machining mechanism of HF-EDAM under different machining parameters is revealed. At the same time, the mechanism of flexible electrodes and EDAM tools has also been studied in depth. The experimental results show that compared with CM, HF-EDAM greatly reduces cutting force and tool wear. In this paper, the excellent machinability of the HF-EDAM machining method based on flexible electrodes is verified by experiments, which provides an effective method for high-quality and efficient machining of titanium alloys.

NOMENCLATURE

N = spindle speed
f = feed rate
C = capacitances

1. Introduction

Titanium alloys are attractive materials because of their corrosion resistance, high specific strength, low density, and good mechanical properties, which are widely used in high-end fields such as aerospace, chemical energy, and medical devices [1-2]. However, due to the disadvantages of low heat transfer coefficient, high chemical activity and large friction coefficient, titanium alloy is easy to produce temperature gradient in conventional machining, resulting in low machining efficiency and poor machining surface integrity. It is a typical difficult machining material [3]. In this context, in order to improve the machinability of titanium alloys, various hybrid machining methods have emerged.

There are many kinds of hybrid machining methods. Compared with conventional processes, the use of hybrid machining methods can effectively improve the machining efficiency, tool life and workpiece surface integrity [4-5]. Niu et al. [6] investigated longitudinal torsional ultrasonic vibration milling of titanium alloys (Ti-6Al-4V) and conducted orthogonal experiments to evaluate the effect of parameters on machining results. Studies have shown that ultrasonic vibration-assisted milling is an effective way to machine titanium alloys, and its machining efficiency and surface quality have been improved to a certain extent, especially to obtain surface compressive stress.

Yadav and Yadava [7] proposed a process for electrical discharge drilling (EDD) to machine aerospace titanium alloy materials and used a new hybrid modeling approach to determine material surface removal rate (MRR), average surface roughness (Ra) and average roundness (Ca) and other results to optimize. It was found that compared with the traditional EDM, the MRR increased by 30.80%, the Ra increased by 24.81%, and the Ca increased by 26.09% after using the EDD hybrid machining method. Ayed et al. [8] investigated a new process for laser-assisted machining (LAM) of Ti-6Al-4V and compared experiments and simulations. The research results show that LAM can effectively reduce the cutting force, and can significantly improve the productivity by optimizing the cutting conditions. However, ultrasonic vibration machining faces the disadvantages of poor surface roughness and machining accuracy at the same time.

In this study, a new method for HF-EDAM based on flexible electrodes is presented. Taking advantage of its unique properties of flexibility and mesh structure, a special new tool has been designed. The machining mechanism of flexible electrodes in the HF-EDAM process is discussed in depth. By comparing with CM and HF-EDAM with non-flexible electrodes, the cutting force and tool wear of the HF-EDAM process based on flexible electrode under different machining parameters were studied.

2. Experimental details

2.1 The principle of HF-EDAM based on flexible electrode

Fig. 1 shows a schematic diagram of the HF-EDAM process based on flexible electrodes. Fig. 1(a) shows the EDM process of the HF-EDAM process. The flexible electrode forms a stable discharge gap with the surface of the workpiece, and the machined material is softened by EDM and converted into a free-cutting layer (recast layer + heat-affected layer). Fig. 1(b) shows the milling process of the HF-EDAM process. The free-cutting layer and a small amount of matrix are removed by milling. The EDM-assisted action in the EDAM process can effectively reduce the cutting force and extend the tool life [9].

Equation (1) gives the relationship between the spindle speed N and the activation time t_{change}, and Equation (2) gives the relationship between the spindle speed N and the discharge time $t_{discharge}$:

$$t_{change} = \frac{\alpha \times 60}{2\pi \times N} \#(1)$$

$$t_{discharge} = \frac{\beta \times 60}{2\pi \times N} \#(2)$$

α is the angle between the carbide insert and the discharge electrode, and β is the angle between the electrodes. Therefore, the adjustment of the discharge time is inseparable from the electrode size. In order to fully improve the EDM time in the HF-EDAM process and take into account the problems of tool chip removal, the electrode ratio of the new HF-EDAM tool based on flexible electrodes is about 75%.

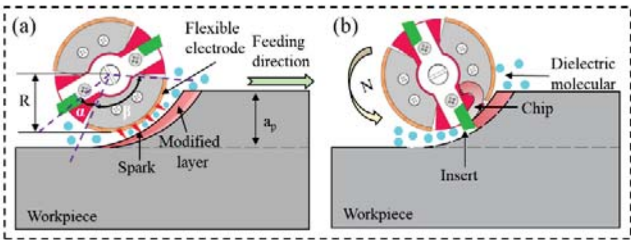

Fig. 1 Schematic diagram of HF-EDAM process with flexible electrode: (a) EDM process and (b) milling process

2.2 The experimental equipment

Fig. 2 shows a photo of the HF-EDAM system and the HF-EDAM specific tool. The HF-EDAM special tool has been designed and manufactured. Because the middle plastic is insulated, the spark current on the tool holder will not discharge the milling insert, which greatly increases the tool life. Copper electrodes and inserts can be fixed with ordinary steel bolts without insulation treatment. At the same time, the bottom screw can adjust the tightness of the flexible electrode to control the radial depth of the electrode. Compared to previous EDAM tool [9], the new HF-EDAM tool based on flexible electrodes has a huge improvement in design, making up for many shortcomings.

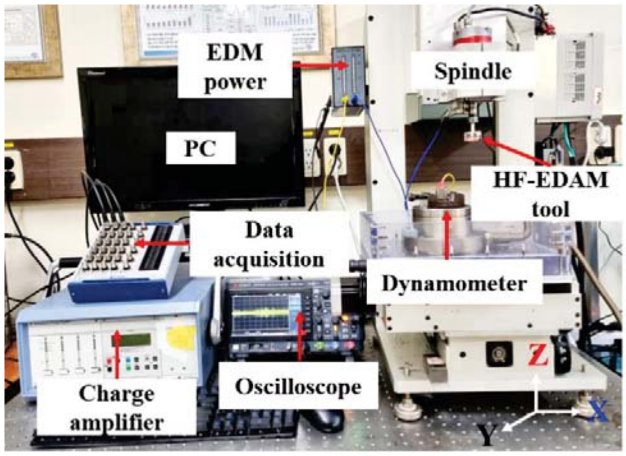

Fig. 2 The HF-EDAM system

The parameters used during the experiment are shown in Table 1. To compare the effect of different discharge energies on the experimental results, three different capacitances (10,000, 100,000 and 1,000,000pF) were selected. In the RC-transistor hybrid circuit, $T_{\mathrm{on-time}}$ refers to the time to turn on the transistor, and its usage range is 3~5 μs. In this paper, $T_{\mathrm{on-time}}$ chooses 4 μs. $T_{\mathrm{off-time}}$ is the turn-off time of the transistor. During the experiment, enough $T_{\mathrm{off-time}}$ is needed to charge the capacitor.

Table 1 Experimental parameters using in HF-EDAM

Items	Values
Spindle speed	3000 rpm
Feed rate	10, 40 and 70 μm/tooth
Radial depth	0.15 mm
Axial depth	1.5 mm
Capacitances (C)	10000, 100000 and 1000000 pF
Voltage	0, 220 V
On-time	4 μs
Off-time	30, 300, 3000 μs

3. Results and discussion

3.1 Cutting force

Fig. 3 shows the cutting force results after CM and HF-EDAM, including cutting forces in different directions (Fx, Fy, Fz) and resultant cutting force (Fr). Due to the chatter of the machine tool, a filter method is used for the final value of the cutting force to reduce noise interference. In order to improve the measurement accuracy, the cutting force under each parameter was recorded three times, and the average value was taken as the final cutting force value.

During this process, three different feed rates (f = 10, 40, 70 mm/min) were compared and analyzed, the intermediate value of the capacitance is 100,000 pF, and the spindle speed is 3000 rpm. It can be seen from Fig. 3(a), (b), (c) and (d) that as the feed rate increases, the results of cutting forces Fx, Fy, Fz and Fr also increase.

At the same time, the cutting force after HF-EDAM is smaller than that of CM due to the EDM assisted effect of HF-EDAM. When the feed rate is small, the cutting force reduction effect of HF-EDAM is more significant than that of CM. This is because when the feed rate is small, the time of the EDM is relatively longer. It can be seen that the lower the feed rate, the more obvious the advantages of HF-EDAM.

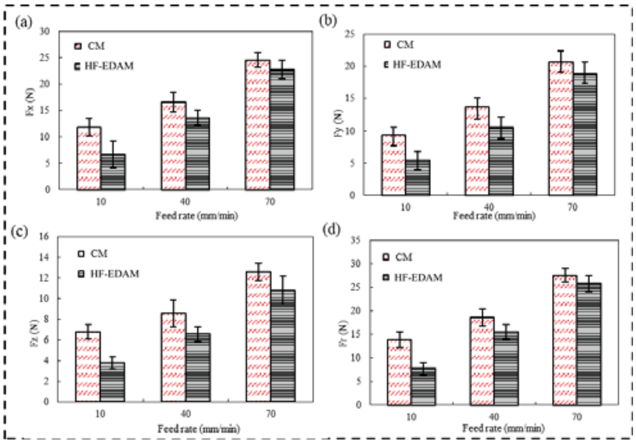

Fig. 3 Measurement results of cutting force in CM and HF-EDAM: (a), (b), (c) and (d) indicate the cutting force of Fx, Fy, Fz and Fr at different feed rates

3.2 Tool wear

As shown in Fig. 4, as the machining distance increases, the tool wear of CM relative to HF-EDAM is more severe. This is because the severe friction between the titanium alloy and the cutting edge will scratch the cutting edge, and the peeling of the coating will increase the radius of the blunt circle. As the cutting edge becomes dull, the mechanical interaction between the tool flank and the workpiece becomes more severe, and tool wear increases rapidly. When machining to 4500 mm, the tool after CM was fractured, while the HF-EDAM tool could still be used normally. The reason for this is that HF-EDAM can effectively reduce the cutting force through the assistance of EDM, which can effectively reduce mechanical and thermal loads compared to CM. It can be seen that the service life of the tool can be effectively improved by the HF-EDAM method based on the flexible electrode.

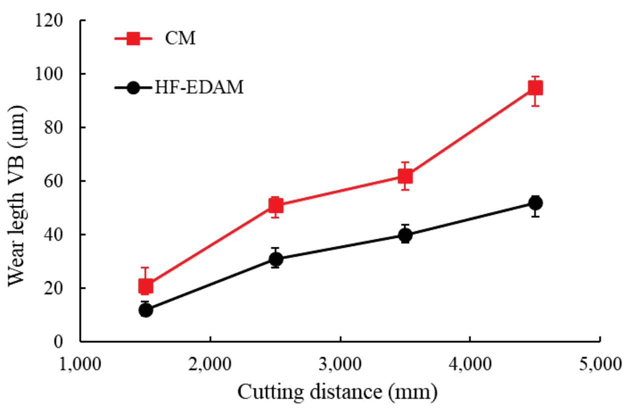

Fig. 4 Tool wear rate of CM and HF-EDAM with change in machining length. (f = 10 mm/min, N = 3000 rpm, C=100,000 pF)

Figure 5 shows the tool wear pictures of CM and HF-EDA M after machining 4500mm. It can be clearly seen that the tool wear of CM is more severe than that of HF-EDAM. This is b ecause the EDM assistance in the HF-EDAM process effectively reduces the cutting force and cutting heat, thereby successfully increasing the tool life.

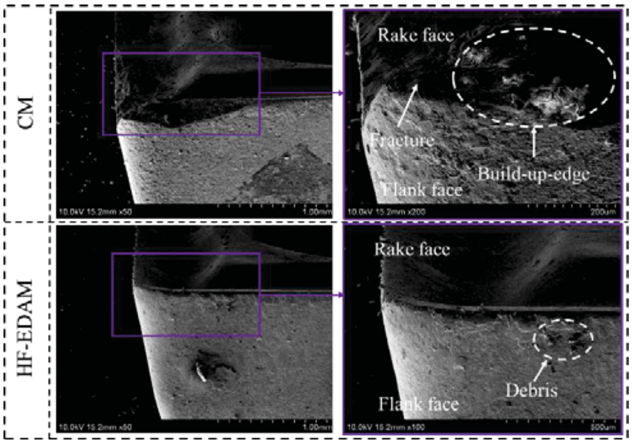

Fig. 5 The tool wear SEM pictures of the two machining meth ods (CM and HF-EDAM) after machining 4500 mm

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