Experimental study on cutting speed and surface roughness of pure copper in WEDM

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Abstract. Wire electrical discharge machining (WEDM) is an important way to manufacture copper electrode. In order to quickly manufacture copper electrode with good surface quality, the influence of electrical parameters on cutting speed and surface roughness of pure copper in wire electrical discharge machining was investigated. An analytical method was proposed to analyze the influence law from the aspects including discharge energy, the formation of adhesive substance on cutting surface and the discharge of electric erosion products. The results show that the pulse width has the greatest influence on the surface roughness and the peak current has the greatest influence on the cutting speed. Using the proposed analytical method, the influence relationship between the electrical parameters and the process objectives could be accurately analyzed, and then the actual production could be guided to select the appropriate electrical parameters according to the optimal process objectives pursued.

1. Introduction

As pure copper showed excellent machining stability, it is widely used in EDM. Scholars have carried out studies on the application of pure copper electrode in EDM. Kumar [1] studied the mechanism of copper electrode wear in Ti6Al4V EDM processing. Phenomenon of tool wear during EDM operation was interpreted with carbide formation at the bottom surface of the tool electrode. Gostiimirovic [2] used copper electrode to investigate the influence of discharge energy during the micro-EDM process of manganese-vanadium tool steel. The results revealed that MRR increased with the increase of discharge energy. Kadirvel [3] Experiments have been carried out in micro-EDM of machining EN24 die steel with different electrodes such as tungsten, copper, copper tungsten, and silver tungsten. The results revealed that the copper electrode achieved maximum MRR. Singh [4] investigated the machining performance of EN-31 tool steel with various electrodes and concluded that copper is the suitable electrode as it exhibited high MRR, good surface finish, minimum electrode wear. It can be seen that pure copper electrode plays an important role in EDM.

In WEDM, most of the rough cutting with a faster cutting speed as the best process objective, and most of the finishing with a smaller cutting surface roughness as the best process objective, while sometimes need to consider cutting speed together with cutting surface roughness as the best process objective. Scholars have made some achievements for the experimental research on the process law of WEDM. Gong [5] studied the cutting performance of TC2 in WEDM, concluded that the peak current has the greatest effect on the processing time and cutting surface quality. Kuriachen [6] studied the cutting performance of Ti6Al4V in micro-WEDM, found that the capacitance has the greatest impact on material removal rate and cutting surface roughness. Jaafar [7] studied the influence of electrical parameters on cutting surface roughness of 2379 steel in WEDM, found that the pulse width gives a...
significant impact on surface roughness. Obviously, the influence of electrical parameters on the process objective is not the same for different materials in WEDM. Scholars studied cutting performance mainly focus on titanium alloy and die steel materials in WEDM, but the research on electrode materials is quite few.

In this paper, pure copper electrode was taken as the experiment material, and the influence law of electrical parameters on cutting speed and surface roughness was analyzed from the aspects of discharge energy, the formation of adhesive substance on cutting surface, and the discharge of electric erosion products, so as to guide the actual production to select appropriate electrical parameters according to the optimal process objectives pursued.

2. Experimental design
The pulse width, pulse interval, peak current and gap voltage in the main electrical parameters of WEDM were selected as the experiment factors, and the electrical parameters were set according to the principle of stable cutting, as shown in Table 1. The single factor variable experiment method was used to study the influence of each experiment parameter on cutting speed and surface roughness.

| Parameters                  | Values |
|-----------------------------|--------|
| Pulse width $T_{on}(\mu s)$ | 10 20 30 40 |
| Pulse interval $T_{off}(\mu s)$ | 30 40 50 60 |
| Peak current $I_p$          | 5 6 7 8 |
| Gap voltage $U$             | 5 6 7 8 |

Note: The values of peak current $I_p$ and servo voltage $U$ in the table only represent the corresponding gear, non-parameter actual value. The higher the gear, the larger the actual value of the corresponding parameter.

Considering the wear of the wire in the HS-WEDM process of AR2300, $\varphi 0.18 mm$ molybdenum wire was replaced before this experiment. In each parameter setting state, two cuts were made according to the sequence of experiment number 1-13, 13-1 (as shown in Table 2) to reduce the experiment error caused by electrode wire wear and other random interference factors.

The experiment material is pure copper, which cutting slit length is 20mm and the thickness is 5mm. The result of the experiment is shown in Figure 1.

The surface roughness of each slit was measured using TR210 hand-held roughness meter for three times, and the average value of the measured data for six times was taken as the surface roughness value under this parameter setting. The morphology of cutting surface was observed on VMU432 image measuring instrument. The cutting speed of each experiment was the ratio of the cutting surface area to the cutting time recorded by the machine tool.

3. Results and Discussion
According to the experimental design, the WEDM experiment of pure copper material with 13 sets of electrical parameters was completed. The data of the experiment results are shown in Table 2.

![Figure 1. Result of the experiment](image-url)
Table 2. The data of the experiment results

| Experiment number | Pulse width Ton (µs) | Pulse interval Toff (µs) | Peak current I_p (A) | Gap voltage U (V) | Cutting speed V (mm²/min) | Surface roughness Ra (µm) |
|-------------------|----------------------|--------------------------|----------------------|------------------|--------------------------|--------------------------|
| 1                 | 10                   | 40                       | 6                    | 6                | 26.91                    | 3.474                    |
| 2                 | 20                   | 40                       | 6                    | 6                | 42.86                    | 4.879                    |
| 3                 | 30                   | 40                       | 6                    | 6                | 43.80                    | 6.353                    |
| 4                 | 40                   | 40                       | 6                    | 6                | 27.27                    | 6.533                    |
| 5                 | 20                   | 30                       | 6                    | 6                | 42.25                    | 5.643                    |
| 6                 | 20                   | 50                       | 6                    | 6                | 35.50                    | 4.774                    |
| 7                 | 20                   | 60                       | 6                    | 6                | 30.00                    | 4.531                    |
| 8                 | 20                   | 40                       | 5                    | 6                | 32.26                    | 4.400                    |
| 9                 | 20                   | 40                       | 7                    | 6                | 45.80                    | 5.960                    |
| 10                | 20                   | 40                       | 8                    | 6                | 50.85                    | 5.920                    |
| 11                | 20                   | 40                       | 6                    | 5                | 25.44                    | 6.108                    |
| 12                | 20                   | 40                       | 6                    | 7                | 37.74                    | 4.244                    |
| 13                | 20                   | 40                       | 6                    | 8                | 35.29                    | 4.014                    |

3.1. Effect of pulse width Ton on cutting speed and surface roughness

The experiment with setting Toff=40µs, I_p=6, U=6, Ton values 10µs, 20µs, 30µs, 40µs according to experiment number 1-4 of Table 2 was carried out. The influence of pulse width Ton on cutting speed and surface roughness is shown in Table 2. The difference between the fastest cutting speed and the slowest cutting speed is 16.89mm²/min, and the difference between the best surface roughness and the worst surface roughness is 2.988µm. The influence law is shown in Figure 2, and the cutting surface morphology is shown in Figure 3.

Figure 2. Effect of pulse width on cutting speed and surface roughness

Wire reversing marks would be left on the cutting surface due to the reversal of electrode wires in HS-WEDM, as shown in Figure 3. The larger the distance between two wire reversing marks was, the larger was the area of cutting in the same time, namely the cutting speed was higher.

L₂ (Ton=20µs), L₃ (Ton=30µs) are significantly larger than L₁ (Ton=10µs) and L₄ (Ton=40µs) as shown in Figure 3, which is consistent with the effect of pulse width on cutting speed as shown in Figure 2. When the pulse width Ton are 20µs and 30µs, a better cutting speed can be obtained. The single pulse discharge electric energy is small with Ton=20µs, restricting the cutting speed. The single pulse discharge electric energy is very large with Ton=40µs, and the rapid electrical erosion can be carried out theoretically, but the pulse width Ton is relatively small compared with the pulse interval Toff under this parameter, so the electrical erosion products cannot be discharged in time, which leads to the instability of the machining process and affecting the cutting speed.
It can be seen from Figure 2 that the surface roughness basically increases with the increase of pulse width $T_{on}$. Increasing the pulse width $T_{on}$, the single pulse discharge electric energy increases, and the diameter of the cutting surface discharge pit increases, but the discharge time of the electrical erosion products decreases relatively, resulting in burns on the cutting surface and generates the adhesive substance on the cutting surface as shown in Figure 3, which comprehensively affects the increase of the surface roughness.

3.2. Effect of pulse interval $T_{off}$ on cutting speed and surface roughness

The experiment with setting $T_{on}=20\mu s$, $I_p=6$, $U=6$, $T_{off}$ values 30μs, 40μs, 50μs, 60μs according to experiment number 5, 2, 6, 7 of Table 2 was carried out.

The influence of pulse interval $T_{off}$ on cutting speed and surface roughness is shown in Table 2. The difference between the fastest cutting speed and the slowest cutting speed is 12.86mm$^2$/min, and the difference between the best surface roughness and the worst surface roughness is 1.112μm. The influence law is shown in Figure 4, and the cutting surface morphology is shown in Figure 5.

![Figure 4. Effect of pulse interval on cutting speed and surface roughness](image1)

![Figure 5. Cutting surface morphology under different pulse intervals](image2)

The single pulse discharge electric energy is unchanged when the pulse width $T_{on}$ is constant with the peak current $I_p$.

When the pulse interval $T_{off}$ increases from 30μs to 40μs, it is known from Figure 4 that the cutting speed increases, because although the pulse interval increases and the average discharge energy decreases per unit time, the discharge of the electric erosion products gradually becomes better and the discharge process is stable, so the cutting speed increases temporarily, and the trend of better surface quality is also more obvious.

According to Figure 5, when the pulse interval $T_{off}=30\mu s$, the main factor affecting the surface roughness is the adhesive substance generated on the cutting surface. When the pulse interval $T_{off}$ is increased from 40μs to 60μs, the discharge machining is relatively stable in this process, and the reason why the cutting speed decreases greatly is the decrease of the average discharge energy per unit time, and the cutting surface quality is basically stable.

3.3. Effect of peak current $I_p$ on cutting speed and surface roughness

The experiment with setting $T_{on}=20\mu s$, $T_{off}=40\mu s$, $U=6$, $I_p$ values 5, 6, 7, 8 according to experiment number 8, 2, 9, 10 of Table 2 was carried out.

The influence of peak current $I_p$ on cutting speed and surface roughness is shown in Table 2. The difference between the fastest cutting speed and the slowest cutting speed is 18.59mm$^2$/min, and the difference between the best surface roughness and the worst surface roughness is 1.560μm. The influence law is shown in Figure 6, and the cutting surface morphology is shown in Figure 7.
Figure 6. Effect of peak current on cutting speed and surface roughness

The single pulse discharge electric energy increases with the increase of peak current \( I_p \). It is known from Figure 6 that the cutting speed increases faster and the surface roughness becomes slightly worse when the peak current \( I_p \) increases from 5 to 6. This process is stable, the discharge of the electric erosion products is unobstructed. The average discharge energy per unit time increased to make cutting speed increase quickly, and the diameter of the cutting surface discharge pit increases, which makes the surface roughness become larger.

The cutting speed and surface roughness continue to increase with the increase of average discharge energy per unit time when the peak current \( I_p \) increases from 6 to 7.

When the peak current \( I_p \) increases from 7 to 8, the single pulse discharge electric energy increases, and the cutting speed continues to increase, but the surface roughness remains basically unchanged. This is because when the cutting speed increases to a certain extent which can achieve rapid cutting, the discharge energy allocated to the cutting surface is basically unchanged, so the diameter of the discharge pit on the cutting surface is basically unchanged.

In this section, the pulse width \( T_{on}=20\mu s \), the pulse interval \( T_{off}=40\mu s \), and the cutting speed is relatively fast, which can ensure the discharge smoothly of the electric erosion products and the steady processing in WEDM.

According to Figure 7, it is known that there is no adhesive substance on the cutting surface after the experiment in this section, and the larger diameter of the discharge pit on the cutting surface is the main reason for the increase of the surface roughness.

3.4. Effect of gap voltage \( U \) on cutting speed and surface roughness

The experiment with setting \( T_{on}=20\mu s \), \( T_{off}=40\mu s \), \( I_p =6 \), \( U \) values 5, 6, 7, 8 according to experiment number 11, 2, 12, 13 of Table 2 was carried out.

The influence of gap voltage \( U \) on cutting speed and surface roughness is shown in Table 2. The difference between the fastest cutting speed and the slowest cutting speed is 17.42 mm\(^2\)/min, and the difference between the best surface roughness and the worst surface roughness is 2.094 \( \mu m \). The influence law is shown in Figure 8, and the cutting surface morphology is shown in Figure 9.
The average discharge energy per unit time remains constant when pulse width $T_{on}$, pulse interval $T_{off}$, and peak current $I_p$ are invariant.

The gap voltage $U$ mainly determines the size of the feed speed in WEDM, too large or too small will affect the cutting speed. It can be seen from Figure 8 that the feed speed is too large when the gap voltage $U=5$, and the short circuit is easy to occur, which is not conducive to the discharge of the electric erosion products, resulting in unstable discharge processing and low cutting speed. Given that the discharge energy allocated to the cutting surface is large, and adhesive substance remains on the cutting surface as shown in Figure 9, resulting in larger surface roughness.

The cutting speed is the maximum when the feed speed basically matches the erosion speed with the gap voltage $U=6$. The feed speed decreases gradually with the gap voltage $U$ increases from 6 to 8, leading to the slow cutting speed and easy to appear open circuit, which is beneficial to the discharge of electric erosion products, so the surface roughness tends to decrease gradually.

4. Conclusions

By controlling the single factor variable experiment method, the influence of each electrical parameter on cutting speed and surface roughness could be studied accurately. Draw the following conclusions:

(1) The peak current has the greatest influence on the cutting speed, and the cutting speed increases obviously with the increase of the peak current. The maximum cutting speed can reach 50.85 mm²/min with $I_p=8$. Secondly, the degree of influence successively is gap voltage, pulse width, and pulse interval. The corresponding maximum cutting speed could be achieved with $U=6$, $T_{on}=30\mu s$, $T_{off}=40\mu s$, respectively. Too big or too small cannot achieve the maximum cutting speed.

(2) The pulse width has the greatest influence on the surface roughness, and the surface roughness increases obviously with the increase of the pulse width. The optimal surface roughness can reach 3.474μm with $T_{on}=20\mu s$. Secondly, the degree of influence successively is gap voltage, peak current, and pulse interval. The surface roughness decreases with the increase of gap voltage, pulse interval, and increases with the increase of peak current.

(3) It is easy to generate the adhesive substance on cutting surface when cutting viscous material of pure copper, which aggravates the deterioration of the surface roughness. The influence of electrical parameters on cutting speed and surface roughness is mutually restricted. The influence law of electrical parameters on cutting speed and surface roughness can be analyzed from the aspects of discharge energy, the formation of adhesive substance on cutting surface and the discharge of electric erosion products, so as to guide the actual production to select appropriate electrical parameters according to the optimal process objectives pursued.

(4) Pure copper has the characteristics of low melting point, good electrical conductivity, and high viscosity, its cutting speed is faster than that of cemented carbide [8] and die steel [9], but the surface roughness is worse than that of cemented carbide and die steel.
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