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# The Effect of High Frequency Pulse on the Discharge Probability in Micro EDM

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**Abstract.** High frequency pulse improves the machining efficiency of micro electric discharge machining (micro EDM), while it also brings some changes in micro EDM process. This paper focuses on the influence of skin-effect under the high frequency pulse on energy distribution and transmission in micro EDM, based on which, the rules of discharge probability of electrode end face are also analysed. On the basis of the electrical discharge process under the condition of high frequency pulse in micro EDM, COMSOL Multiphysics software is used to establish energy transmission model in micro electrode. The discharge energy distribution and transmission within tool electrode under different pulse frequencies, electrical currents, and permeability situation are studied in order to get the distribution pattern of current density and electric field intensity in the electrode end face under the influence of electrical parameters change. The electric field intensity distribution is regarded as the influencing parameter of discharge probability on the electrode end. Finally, MATLAB is used to fit the curve and obtain the distribution of discharge probability of electrode end face.

## 1. Introduction
Micro EDM introduces the principle of conventional EDM to the field of micromachining by reducing the energy of discharge machining and servo control. Short pulse duration and high frequency pulse power supply is used in micro EDM to ensure a small amount of energy of single pulse processing to achieve the machining accuracy and in the meanwhile improve the efficiency of processing. As micro EDM is significantly influenced by the electrical parameters, the process of machining is bound to be influenced by the impact mechanism from the high frequency pulse power supply. M T Yan et al.[1] presented the development of a high frequency power supply for surface quality improvement of wire electrical discharge machining (wire-EDM). A novel fixed pulse-width modulation pulse control method was proposed to generate high frequency and short-duration pulse control signals. X Li et al.[2] studied the wear mechanism of Ni-TiN/Cu composite electrode in the case of high frequency pulse current, and the influence of the fluctuation frequency of discharge current on electrode wear in micro-EDM was found out. D K Chung et al.[3] developed a new high frequency bipolar pulse generator for micro EDM in order to prevent electrolytic corrosion. Using the new pulse generator, micro holes without electrolytic corrosion were successfully fabricated in deionized water and tap water. R Casanueva et al.[4] found a new application of the resonant converter in EDM power supply, which is designed for the purpose of developing small size EDM systems. By tuning the conversion frequency to the natural resonant frequency an optimum and stable operation using tap water as dielectric fluid was achieved preventing the generation of undesired impulses and keeping the distance between the

electrode and the workpiece within the optimum stable range. Q Liu et al.[5] discussed the influences of tool electrode diameter on the micro-EDM process based on the skin-effect and area effect. It is demonstrated that the machining speed, electrode wear, and taper rate are different with the increase of tool electrode diameter. Y W Yong et al.[6] experimentally verified the electromagnetic properties of plasma under the condition of skin-effect, which was used to study the effect of electromagnetic field on machining mechanism in discharge channel of EDM. B Schacht et al.[7] studied the effect of pulse frequency on resistance of the wire electrode under the skin-effect of wired EDM and explained the importance of the skin-effect to high frequency wired EDM. Y Liu et al.[8] based on the theory of skin-effect studied the principle of the electrode energy distribution of RC circuit and the variation law of discharge location, and achieved the EDM machining of freeform surfaces.

In this paper, the effect of pulse frequency, electrical current and permeability on the skin-effect under high frequency pulse and the skin-effect on discharge probability in the process of micro EDM are explored. The principle of skin-effect in high frequency electromagnetic field is applied to the analysis of micro EDM discharge process.

## 2. The skin-effect in high frequency pulse EDM
The skin-effect is a phenomenon that affects the energy distribution of electromagnetic fields caused by the frequency variation of the electromagnetic field, which is more significant in high frequency conditions. It is found that the strength of the skin-effect can be reflected by the skin depth. The expression for skin depth $\delta$ is:

$$\delta = \sqrt{\frac{2}{f\mu\sigma}} \tag{1}$$

where, $f$ is frequency of pulse, $\mu$ is magnetic conductivity, and $\sigma$ is electrical conductivity.

The influence of the skin-effect on micro EDM is mainly to change the distribution of electric energy within the electrode. Due to that the energy distribution directly affects the discharge probability of electrode discharge location, so the skin-effect indirectly affects the electrode discharge location. Skin-effect will promote the location of discharge distributing on the electrode edges, which leads to a fast consumption of the electrode edges in the machining process.

## 3. The micro electrode energy transfer model under high frequency pulse

### 3.1. Establishment of mathematical model
When the electrode is applied to a high frequency pulse current and the spark discharge occurs, a changing magnetic field whose direction is perpendicular to the current is generated inside and outside of the electrode. That the electric field and the magnetic field excite each other can be expressed by the Maxwell equation of the time-varying field [9].

The relationship between electric field strength $E$ and electric potential $V$ is:

$$E = -\nabla V \tag{2}$$

The relationship between transient current density J and electric field E is:

$$J = \sigma E + \varepsilon_0 \varepsilon \frac{\partial E}{\partial t} \tag{3}$$

where, $\varepsilon_0$ is vacuum dielectric constant. The instantaneous variational current can generate induced magnetic field, which is shown as:

$$\begin{cases} \sigma \dfrac{\partial A}{\partial t} + \nabla \cdot (\mu^{-1}B) = J \\ B = \nabla \cdot A \end{cases} \tag{4}$$

where, $A$ is the magnetic field vector. The strength of the induced electric field $E_i$ is calculated according to the variation of magnetic field as:

$$E_i = -\frac{\partial A}{\partial t}$$

(5)

*3.2. Establishment of the micro electrode energy transfer simulation model*
The simulation software COMSOL Multiphysics is used to simulate the discharge process of EDM at a high frequency pulse. The simulation method of magnetic field and electric field coupling is used when modelling, and then the 3D steady state and frequency domain simulation is performed.
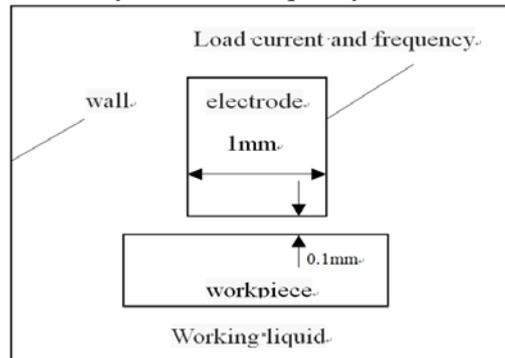


**Figure 1.** Simulation model of EDM

The micro electrode energy transfer model includes a 1mm diameter tool electrode, workpiece and the surrounding insulation working fluid, as shown in Figure 1. After loading pulse and current on the whole electrode, the electric field intensity between the electrode and the workpiece can be up to $1.2 \times 10^7$ V/m, which is pretty consistent with the actual EDM.

**4. Simulation and result analysis**
The simulation of energy distribution is carried out under different pulse frequency, electrical current and magnetic permeability with COMSOL Multiphysics simulation software. The simulation parameters in three groups are shown in Table 1.

**Table 1.** The simulation parameter list

|   | material | Pulse frequency(kHz) | electrical current(A) | Magnetic permeability(H/m) |
|---|----------|---------------------|----------------------|----------------------------|
| 1 | copper | 500,1000 | 20 | 1 |
| 2 | copper | 500 | 20,40 | 1 |
| 3 | copper, iron | 500 | 20 | 1,400 |

*4.1. The simulation results and analysis of different pulse frequencies*
Figure 2 shows the current density distribution of the copper electrode under the conditions as I = 20 A, f = 500 kHz and μ = 1 H/m. As shown in Figure 2, the current density distributes non-uniformly within the electrode. The electrode surface has the highest current density value, and current density value is the lowest in the electrode center. This is due to the skin-effect promoting the electrical energy transferring through electrode surface rather than the center.
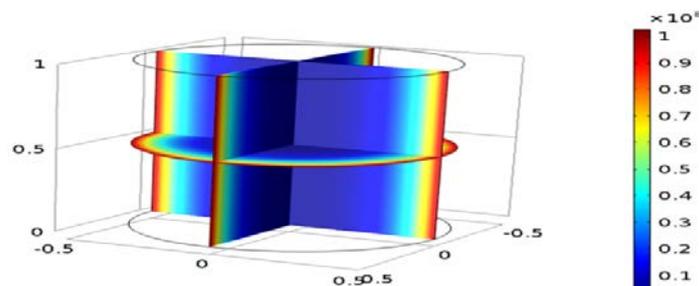


**Figure 2.** The current density distribution **of** the copper electrode

The current density value is derived from the simulation results based on different pulse frequency as 500 kHz and 1000 kHz, the comparison of current density distribution is shown in Figure 3. From the Equation (3), the simulation result can be post-reprocessed, and the electric field intensity distribution can be obtained under different pulse frequencies, as shown in Figure 4.
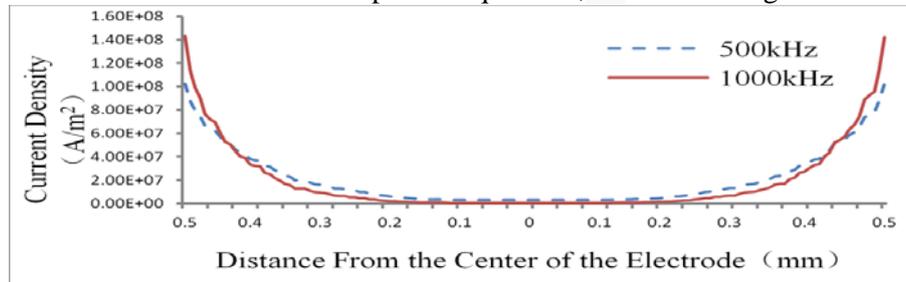


**Figure 3.** Current density comparison chart of the copper electrode at different pulse frequencies
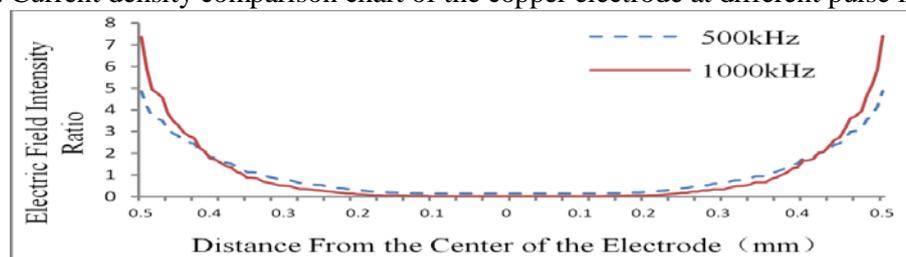


**Figure 4.** Electric field intensity comparison chart of the copper electrode at different pulse frequencies

From Figure 3 and Figure 4, it can be observed that the two curves of the graph resemble the shape of bathtub under the influence of the skin-effect, so they are named as "bathtub curve". As shown in Figure 3 and Figure 4, with the pulse frequency increasing, the electric field intensity and current density are more concentrated on the surface of the electrode, which causes the electric field intensity and current density of the interior of electrode reduced accordingly. Compared the two figures, it is found that there exist intersections of the two curves when the pulse frequency changes. Within a radius of 0.43mm, the current density and electric field intensity is lower when the pulse frequency is 1000kHz. While, in other regions the current density and electric field intensity is higher when the pulse frequency is 1000 kHz. The reason is that the higher the pulse frequency is, the more obvious the skin-effect phenomenon is, so the "bathtub curve" is steeper. Finally, it is concluded that as the pulse frequency increases, the distribution of current density and electric field intensity is more concentrated on the electrode surface. At the same time, the skin depth becomes small, which makes the skin-effect phenomenon more obvious.

*4.2. The simulation results and analysis of different electrical current*
The curves in Figure 5 show that with the double electrical current, the corresponding current density of both the electrode surface and the center is about two times that of the original, though the distribution pattern of the current density is unchanged. The reason is that the current has no effect on the distribution of current density in the electrode. But the larger the current is, the more energy is transmitted in the electrode. Therefore, the current density on the electrode surface is increased.

From Figure 6, it can be seen that when the current changes the ratio of electric field intensity at each point to the average electric field intensity doesn't change and the two curves are identical. This proves once again that the current change has no effect on the distribution of electric field intensity. But the Figure 5 shows that the current density value of the electrode surface is increased, which suggests that although the increase of current does not directly affect the ratio of the electric field intensity distribution, the increase of current density on electrode surface is bound to lead the phenomenon of skin-effect to be more apparent, which will affect the electrode wear of EDM.
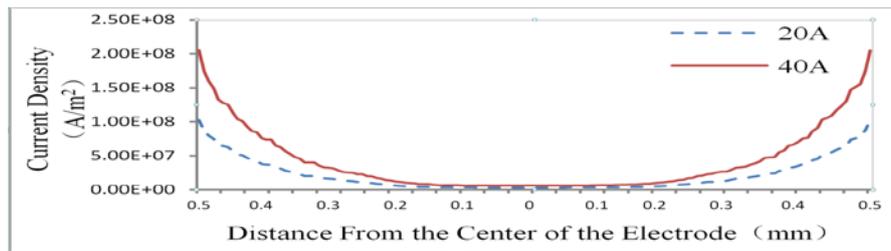
**Figure 5.** Current density comparison chart of the copper electrode at different electrical current
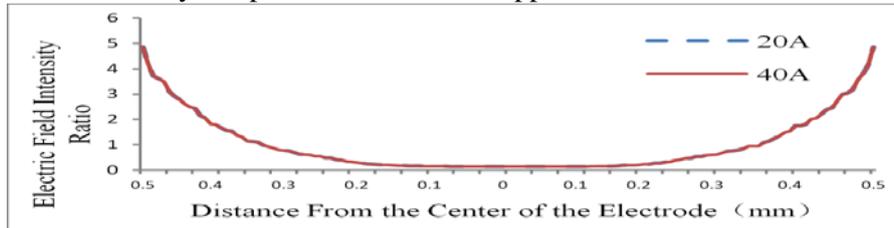


**Figure 6.** Electric field intensity comparison chart of the copper electrode at different electrical current

*4.3. The simulation results and analysis of different magnetic permeability*
By observing the Figure 7, the skin depth of the iron electrode is very small compared with the copper electrode. The reason is that the magnetic permeability of iron is 400 times more than that of copper, and the skin depth reduces with the increase of magnetic permeability. As a result, the skin depth shown in Figure 7 is much smaller than that in Figure 2.
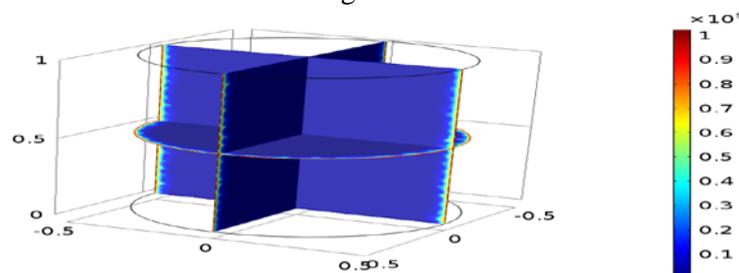


**Figure 7.** The current density distribution of the iron electrode based on magnetic permeability is 400H/m.
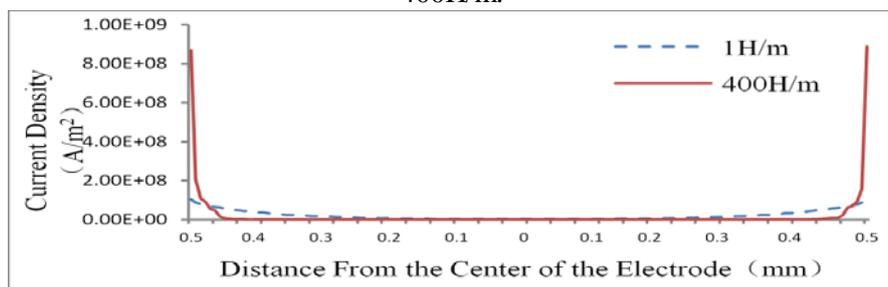


**Figure 8.** Current density comparison chart at different magnetic permeability

Figure 8 and Figure 9 show that the higher the magnetic permeability is, the more obvious the skin-effect phenomenon is, which increases the current density and electric field intensity on the electrode surface. While the distribution of current density and electric field intensity within the electrode decreases with the increase of magnetic permeability, and the greater the magnetic permeability is, the faster the reduction is. This is because after increasing the magnetic conductivity, under the skin-effect, the current is almost all gathered near the surface of the electrode, which causes the current density to decrease inside of the electrode. Meanwhile, the electric field intensity on the

electrode surface increases with the sharp increase of current density on the surface of the electrode. It is concluded that as the magnetic permeability increases, skin-effect phenomenon of the electrode is strengthened obviously, which increases the current density and electric field intensity on the electrode surface, meanwhile decreases the current density and electric field intensity within the electrode.
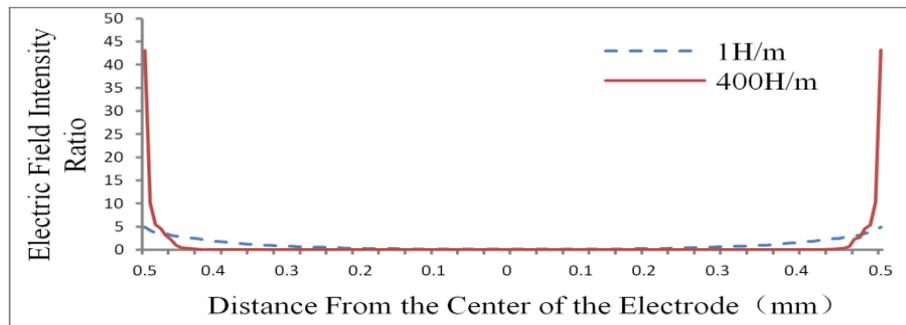


**Figure 9.** Electric field intensity comparison chart at different magnetic permeability

## 5. Calculation of the probability of electrode end face

### 5.1. The fitting of the electric field intensity distribution curve

The method of exponential function to curve fitting is used in MATLAB software to fit the left half of the electric field intensity distribution curve, which is obtained in the case of $I = 20$ A and $f = 500$ kHz with the copper electrode. Then the fitting curve and the curve equation can be obtained. The fitting equation of the two terms exponential function [10] is expressed as follows:

$$f(x) = A \cdot e^{Bx} + C \cdot e^{Dx} \tag{6}$$

where, $A$, $B$, $C$ and $D$ are coefficients. When $A$, $B$, $C$ and $D$ is 0.01272, -9.807, 0.03827 and 5.313 respectively, the fitting degree of is the highest.

After calculation, it can be found that the degree of fit is above 0.99. Therefore, the fitting curve can be used to represent the distribution of the electric field intensity for relevant analysis.

### 5.2. The normalization of the fitting curve

In order to obtain the function of discharge probability, the fitting curve should be normalized. In this paper, the fitting curve is treated by standard normalization method and the fitting curve of discharge probability is obtained as shown in Figure 10.
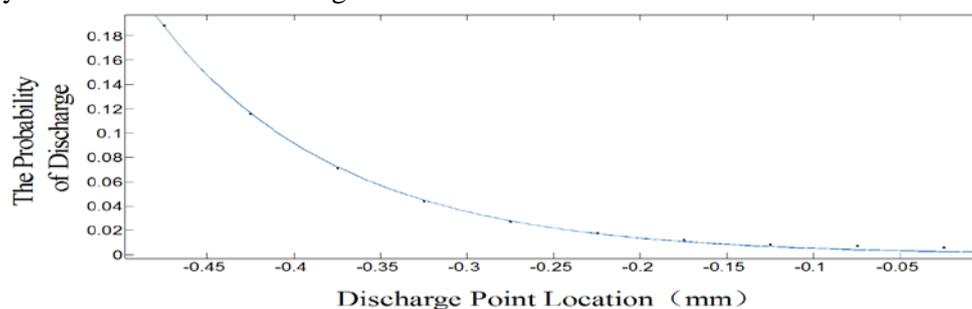


**Figure 10.** The graph of fitting curve of discharge probability

The equation of the discharge probability curve for the whole electrode is:

$$f(x) = 0.001779 \times e^{9.809|x|} + 0.004294 \times e^{-4.186|x|} (-0.5 \leq x \leq 0.5) \tag{7}$$

Discharge probability can be used for simulating random discharge of electrode end face. Combining with the electrode material removal in volume and multiple discharge iterations, the laws of electrode wear and shape change in EDM machining can be revealed.

## 6. Conclusions

In this paper, the distribution laws of electric field intensity and current density on the electrode end face are analyzed under the condition of different pulse frequency, electrical current and magnetic permeability. Based on the distribution curve of electric field intensity, the fitting curve and the curve equation in the direction of the diameter of electrode end face is obtained. Finally, the fitting curve is normalized and the probability of discharge is obtained. The conclusions are as follows:

(1) With the increasing of pulse frequency and magnetic permeability of electrode, the skin-effect phenomenon of the electrode is more obvious, which results in the current density and the electric field intensity more concentrated on electrode surface, also decrease the current density and electric field intensity inside of the electrode. With the increasing of electrical current, there are no effect on the distribution of current density and electric field intensity, but the values of current density and electric field intensity in the whole electrode are increased, which affects the discharge distribution on the surface of electrode end.

(2) The discharge probability at each point along the direction of diameter is symmetric about the center of electrode, and with the change of location, the discharge probability can be expressed by exponential function. The fitting curve and the curve equation of the electric field intensity distribution curve can be used to represent the actual distribution state of the electric field intensity, which can provide the theoretical basis for the further study of the electrode wear law.

## Acknowledgments

## References

[1] Yan  M T, and Liu Y T 2009 Design, analysis and experimental study of a high-frequency    power supply for finish cut of wire-EDM J. *International Journal of Machine Tools & Manufacture* 49(10) pp 793-796

[2] Li X P, Wang Y G, Zhao F L, Hua M,W U and Liu Y 2014 Influence of high frequency pulse on electrode wear in micro-EDM J. *Defence Technology* 10(3) pp 316-320

[3] Chung D K, Hong S S, Min S P and Chong N C 2011 Machining characteristics of micro EDM in water using high frequency bipolar pulse J. *International Journal of Precision Engineering & Manufacturing* 12(2) pp 195-201

[4] Casanueva R, Azcondo F J, Branas C and Bracho S 2005 Analysis, design and experimental results of a high-frequency power supply for spark erosion J. *IEEE Transactions on Power Electronics* 20(2) pp 361-369

[5] Liu Q, Zhang Q, Zhu G, Wang K, Zhang J and Dong C 2016 Effect of Electrode Size on the Performances of Micro-EDM J. *Materials & Manufacturing Processes* 31(4) pp 391-396

[6] Yong Y W, Guo C N and Yang L 2015 Study on EDM Machining Characteristics Based on  Skin Effect and Magnetic Field J. *Machinery Design & Manufacture* (in Chinese)

[7] Schacht B, Kruth J P, Lauwers B and Vanherck P 2004 The skin-effect in ferromagnetic electrodes for wire-EDM J. *The International Journal of Advanced Manufacturing Technology* 23(11) pp 794-799

[8] Liu Y, Sundaram M M, Zhao F L and Rajurkar K P 2011 Study on manufacturing free form surface parts in micro EDM based on skin effect theory J. *High Technology Letters* 17(4) pp 439-445

[9] Shi S, Zhang L and Li J 2007 Time-Varying Electromagnetic Fields and Maxwell's Equations M. Basic Electromagnetism and Materials. *Springer New York pp* 157-171

[10] Du J, Song M, Hu N N, Cao K N, Huang W T and Xu P 2014 A Double Exponential Function Fitting Algorithm for Optimize Parameter of  μ H Curve J. *Advanced Materials Research* 960-961 pp 1146-1150