DISCHARGE CHANNEL GROWTH IN MICRO EDM OF HIGH FREQUENCY PULSE

Liu Yu[1], *Wang Jin*[2], *Wang Yuangang*[3], *Zhao Fuling*[2]

(1. School of Mechanical Engineering, Dalian Jiaotong University, Dalian, 116028, P. R. China;
2. Key Lab for Precision & Non-conventional Machining of the Ministry of Education, Dalian University of Technology, Dalian, 116024, P. R. China;
3. School of Mechanical Engineering, Dalian University, Dalian, 116622, P. R. China)

Abstract: The influences of intense magnetic pinch effect caused by electromagnetic field with high frequency on discharge channel expansion and plasma configuration change are discussed. The change of Lorentz force exerting on charged particles in discharge channel is calculated under the electromagnetic field with high frequency. Through the theoretical analysis and experimental study, the forming process of discharge channel is conjectured. And it is considered that the changes of discharge channel, such as the decrease of diameter and increase of energy density, coming from the intense magnetic pinch effect in high frequency electromagnetic field, are the main reasons for a series of special phenomena on the machined surface in micro EDM.

Key words: micro EDM; discharge channel; high frequency electromagnetic field; magnetic pinch effect; discharge crater

CLC number: TG661 **Document code**: A **Article ID**: 1005-1120(2011)04-0353-09

INTRODUCTION

As a nontraditional machining method, micro EDM is widely used in the field of micro scale[1]. Because of the particularity of its machining mechanism, micro EDM does qualify for the machining of 2-D and 3-D complex structures of special materials[2], such as some difficult-to-cut materials with the properties of high strength, high hardness or high brittleness. Consequently, micro EDM has attracted more and more attentions in fields of aviation, aerospace, electronic communication, biological medicine and mould machining industries[3].

In micro EDM, the method of reducing discharge energy per pulse is adopted to convert conventional EDM into micro machining. In order to improve machining efficiency, short pulse power supplier with high frequency is widely used in micro EDM. However, the applications of these high frequency power supplier cannot drop the machining energy thoroughly, they just refine the energy distribution. The dense arrangement of micro pulse energy brings micro EDM into a new machining environment, i. e., high frequency electromagnetic field. Under the condition of this high frequency and time varying electromagnetic field, the original machining process of EDM will be changed[4]. And further, the precision and quality in micro EDM of micro slots, micro holes and micro components with complex structures which are applied in high-tech fields such as aviation and aerospace, will be influenced.

In this paper, the impacts of high frequency electromagnetic field on micro EDM process are taken into account. The change of magnetic pinch of discharge channel under high frequency discharge and its effects upon the process of electrical discharge are analyzed. And a magnetic pinch physical model of discharge channel in micro EDM is proposed. Finally, the experimental verification is carried out.

Foundation item: Supported by the National Natural Science Foundation of China (50635040).

Received date: 2010-07-22; **revision received date**: 2010-12-15

E-mail: liuyu_ly12@hotmail.com

1 GENERAL DEVELOPMENT PROCESS OF DISCHARGE CHANNEL IN EDM

In EDM, pulse spark discharge instantaneously breaks down the dielectric medium between the closely spaced electrodes, forming the discharge channel. Then a small amount of materials from both tool and workpiece are removed by the electro thermal effect of discharge spark. Through the accumulation of micro amount of removal, the manufacturing of features or parts is achieved.

During the discharge process, the density and temperature gradient inside discharge channel and the speed of particle lateral movement can generate the pressure of plasma external expansion. Meanwhile, the discharge channel is suffered from the restriction of magnetic pinch effect and the pressure of dielectric medium around. Under these constraints, the configuration of discharge plasma changes until it reaches its balance. Thus, the force balance relationship of charged particles is considered as: the expansion pressure of discharge plasma is equal to the summation of the binding effect of self-generated magnetic field and resistance of dielectric fluid, as shown in Fig. 1.

As the discharge channel directly connects with the electrodes , it is the energy source of electrodes in the material removal process. The shape of discharge channel directly affects the process of electrode material removal. In general, the diameter of discharge crater corresponds to that of discharge channel[5]. Besides, there is a wave characteristic of discharge channel[6], which also greatly affects the material removal of electrode. The longitudinal vibration and transverse vibration components of plasma oscillation generate the impact pressure fluctuation on molten electrode materials[7]. The pressure change leading to the thermal explosion of vaporization can extrude or eject the molten materials out of discharge craters.

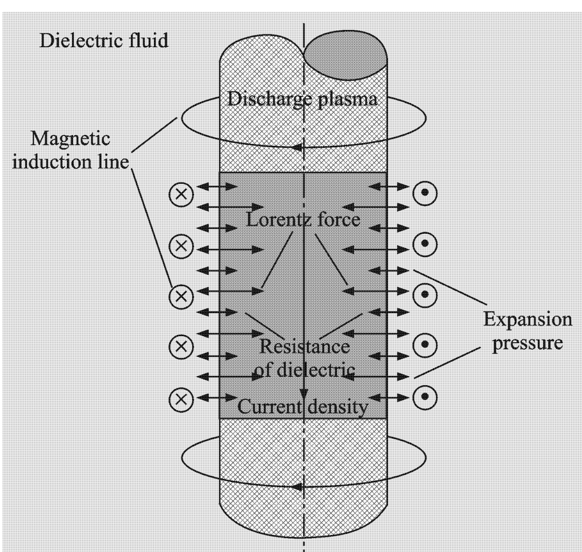


Fig. 1 Relationship of force balance in discharge plasma

2 MAGNETIC PINCH EFFECT UNDER HIGH FREQUENCY PULSES

In micro EDM, to ensure a small removal amount per pulse, the discharge pulse on time is controlled as 5 μs or less, and the pulse off time is reduced accordingly. Therefore, using the nanosecond pulse power supplier, the frequency of discharge pulse can reach the scale of megahertz[8]. In this situation, the influences of high frequency electromagnetic field in micro EDM process have to be considered.

2.1 Calculation of Lorentz force in magnetic pinch

According to the Z-pinch theory in plasma physics, the movement of plasma particles in discharge channel during the discharge process coincides with the particle acceleration under the Lorentz force ($F = \boldsymbol{J} \times \boldsymbol{B}$)[9]. Consequently, the magnetic pinch effect on discharge channel during plasma expansion process is generated from centripetal Lorentz force exerting on the plasma particles, which is also proven in the completely conductive plasma equilibrium equations of static magnetics

$$\nabla P - \frac{1}{c}\boldsymbol{J} \times \boldsymbol{B} = 0 \tag{1}$$

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{J}, \quad \nabla \cdot \boldsymbol{B} = 0 \tag{2}$$

where ∇ is the gradient operator, P the thermal pressure, c the speed of light in vacuum, $\boldsymbol{J}$ the current density and $\boldsymbol{B}$ the magnetic induction intensity. From Eq. (2), the relationship between varying current and its self-generated magnetic field is also obtained.

As to high frequency electromagnetic field, supposing that the discharge plasma is columned with radius of a, the current i through plasma is of sine wave as $i(t)=I_m\sin\omega t$, so that the electric field intensity $\boldsymbol{E}$ and the magnetic induction intensity $\boldsymbol{B}$ are sine function, too. Because of the symmetry property, there are only components of electric field intensity $\boldsymbol{E}$ and current density $\boldsymbol{J}$ along the axis of plasma, and only component of magnetic induction intensity $\boldsymbol{B}$ along the circumferential direction of column. Based on the skin effect in high frequency electromagnetic field, the expressions of current density $\boldsymbol{J}$ and magnetic induction intensity $\boldsymbol{B}$ are respectively given by[10]

$$J_m = \frac{I_m}{2\pi a}\frac{pI_0(pr)}{I_1(pa)} \tag{3}$$

$$B_m = \mu\frac{I_m}{2\pi a}\frac{I_1(pr)}{I_1(pa)} \tag{4}$$

where J_m and B_m are the amplitudes of $\boldsymbol{J}$ and $\boldsymbol{B}$ respectively, $I_k(x)$ is the modified Bessel function of the first kind with k as the order of the function, $p=\sqrt{\mathrm{j}\omega\mu\gamma}$, j the imaginary unit, ω the angular frequency, μ the permeability of material and γ the conductivity of material, r the distance from charged particle to plasma axis. So that, the Lorentz force under skin effect F_s is

$$F_s = J_m \times B_m \tag{5}$$

$$F_s = \frac{\mu I_m^2}{4\pi^2 a^2}\frac{pI_0(pr)\times I_1(pr)}{I_1^2(pa)} \tag{6}$$

According to $p=\sqrt{\mathrm{j}\omega\mu\gamma}$ and $\omega=2\pi f$, Lorentz force F_s is closely related to frequency f. The influences of high frequency electromagnetic field on discharge current and its self-generated magnetic field will change the distribution of Lorentz force in plasma, and further affect the configuration and property of discharge plasma.

2.2 Magnetic pinch effect in micro EDM

Given that the pulse width and pulse interval are equal, convert the continuous square wave pulses commonly used in micro EDM into the expansion of Fourier series as[11]

$$f(t)=\frac{I_m}{2}+\frac{2I_m}{\pi}\left(\sum_{n=0}^{\infty}\frac{1}{2n+1}\sin(2n+1)\omega t\right) \tag{7}$$

Through the method of Fourier series expansion in Eq. (7), mutually independent pulses are analyzed as an entirety of series. In micro EDM with high frequency, this method takes the relativity of each pulse′s effect on discharge machining into account, more conforming to the practice of EDM process.

As the constant part of Eq. (7) remains invariable in the whole machining process, its impact on time varying electromagnetic field can be ignored. And for the Lorentz force with Maxwell equations, total current law and Bessel equations used in derivation process of skin effect obey the superposition principle. Each sine part in Eq. (7) can be substituted into Eq. (6), and solved. Then superpose the results by amplitude proportion of each part, the total Lorentz force F_a is obtained by

$$|F_a| = \left|\frac{2I_m}{\pi}\sum_{n=0}^{\infty}\frac{1}{2n+1}F_{sn}\right| = \frac{\mu I_m^3}{2\pi^3 a^2}\sum_{n=0}^{\infty}\frac{1}{2n+1}\left|\frac{sI_{1n}(\sqrt{\mathrm{j}}\,sr)\times I_{0n}(\sqrt{\mathrm{j}}\,sr)}{I_{1n}^2(\sqrt{\mathrm{j}}\,sa)}\right| \tag{8}$$

The numerical calculation of Eq. (8) is carried out. As it is usually considered that the diameter of discharge channel is close to that of discharge crater, according to the measured result of experiment and under the specific condition that the diameter of discharge crater is approximate to 2.3 μm. For ease of calculation, set the radius of discharge plasma as $a=1.2$ μm, approximate the electric conductivity of plasma to that of metallic conductor, and set the magnetic permeability as around 24 times of vacuum permeability. The peak current of pulse discharge is set as $I_m=1$ A, and different discharge frequencies are set as $f=$ 500, 100, 20 kHz. The numeral calculation result of Lorentz force along the radial direction r of discharge plasma is shown in Fig. 2. From Fig. 2, it can be seen that under the high frequency pulse, the distribution of Lorentz forces along plasma

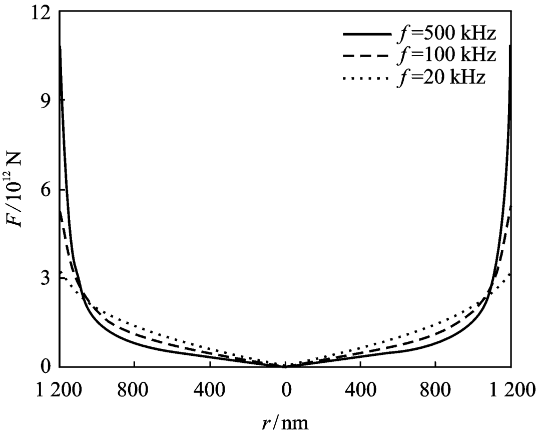


Fig. 2 Distribution of Lorentz force exerting on charged particles in discharge channel under different frequencies

cross section changes significantly, and charged particles at the edge of plasma channel suffer very strong Lorentz forces.

It is needed to indicate that the numeral calculation above is based on the uniform distribution hypothesis of charged particles in discharge channel. Actually, in the cross section of discharge channel the particle density is high at the center and relatively low at the edge of plasma, so that in practice, the Lorentz force is on the low side at the edge. But this does not affect the fact that under the effect of high frequency electromagnetic field, the magnetic pinch effect of discharge plasma is increased remarkably. Of course, the invariant diameter of discharge channel during the whole process is also the prerequisite of the above calculation process. The radius of the discharge channel plasma used in calculation can be regarded as the average plasma radius.

3 INFLUENCES OF HIGH FREQUENCY MAGNETIC PINCH EFFECT ON DISCHARGE CHANNEL

In micro EDM, high discharge frequency increases the magnetic pinch effect during the formation of discharge channel. This will affect the expansion of the plasma, and further, change the spark discharge and material removal model in conventional EDM. The influences of high frequency magnetic pinch effect on micro EDM can be summarized into two aspects. (1) Decreasing the diameter of discharge channel, and increasing the energy per unit area of plasma cross section. (2) Increasing the discharge channel plasma oscillation, bringing instability to plasma configuration balance.

3.1 Influences on plasma configuration

From Fig. 2 it is easy to see that under different frequencies of electromagnetic field, the Lorentz forces on the charged particles along the radial direction of discharge plasma differ remarkably, but the overall trends of Lorentz force distributions are almost the same. In the high frequency electromagnetic field, the electromagnetic energy concentrates near the edge of plasma for the skin effect, where the Lorentz forces on charged particles increase significantly, generally several times or even higher than that of usual condition. The high pressure drives charged particles moving towards the center of plasma rapidly. In this process, powerful magnetic pinch effect is generated compressing the diameter of discharge channel. Besides, in the plasma center, the electromagnetic field is relatively weak, and the difference of electromagnetic field effects between the charged particles in discharge channel center and those near the edge is great. According to the nonuniform electromagnetic field theory, the charged particles have the trend to be pushed from the strong electromagnetic field to the relatively weak one. The larger the difference of electromagnetic energy is between the two electromagnetic fields, the higher the acceleration of particle movement is, accordingly, the magnetic pinch effect of plasma is more significant. While in the condition of low frequency, the magnetic pinch effect of plasma edge is reduced obviously.

In high frequency machining, because of the strong magnetic pinch effect of discharge channel, the expansion of discharge channel is greatly constrained. Under such constraint, the discharge channel is thinner than the channel under the usual conditions with higher particle density and higher thermal energy density. Fig. 3 shows the cross section of discharge channel under the magnetic pinch effect. In Fig. 3(a), the discharge frequency is low, at the edge of plasma the Lorentz forces are weak, and the diameter of discharge channel is large. In Fig. 3(b), high frequency pulses increase the Lorentz force at the edge significantly, forming strong compression of plasma, therefore the diameter of discharge channel becomes small, and accordingly the energy density of discharge channel is increased obviously. Reduced discharge channel cross section decreases thermal effect zone on the surface of both electrodes, causing the decrease of discharge crater section. High particle density in discharge channel deeply concentrates the bombardment action of high speed charged particles on electrode surface, so that the unit area of discharge crater receives more energy, and relatively deep discharge crater is obtained. The high thermal energy density increases the proportion of vaporizing removal, and the effects of vaporization thermal explosion and plasma column implosion increase notably. These are beneficial to the removal of electrode materials.

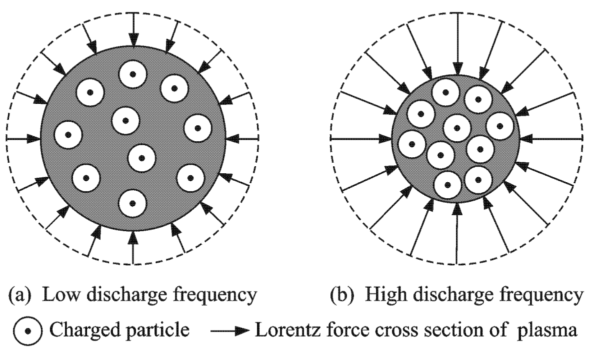


Fig. 3 Cross section of discharge channel under magnetic pinch effect

3.2 Influences on plasma oscillation

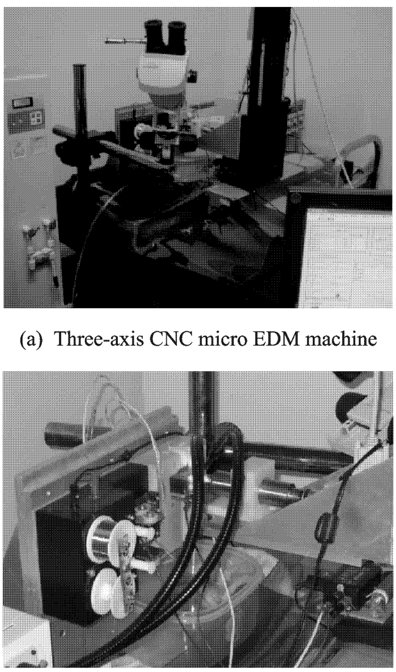
The charged particles with high current density and thermal energy density moving at high speed in a narrow discharge channel bring instability to the configuration balance of plasma. The increase of electron density in discharge channel enhances the longitudinal wave of plasma oscillation. Under the effect of longitudinal vibration, the pressure change on the surface of molten material removes part of material during discharge machining. Meanwhile, the thermal effect and bombardment effect of charged particles in discharge channel are not finished. These repetitive processes from melting and vaporizing materials to impacting and removing materials cause the continuously deepening of discharge crater in a very short period of time. These changes of micro conditions during the discharge process are the key factors to the narrow and deep discharge craters.

Besides discharge channel particles oscillating sparsely and densely under the effect of longitudinal vibration, there also exists the transverse vibration along the direction perpendicular to plasma axis. In addition, with the reducing of discharge channel diameter and the increasing of energy flux density, the probability of plasma transverse vibration will be raised, and its amplitude will be increased accordingly. Rather than fixing firmly at the same location, the center of interface between discharge channel and electrode surface travels randomly within a certain range because of the transverse vibration of plasma. And the residence time of interface center in the local area of electrode surface is unfixed either. Under the high frequency pulses, the plasma oscillation becomes active. The changes of the discharge channel center are shown as the shape changes of discharge craters on the electrode surface after the machining.

As a result, magnetic pinch effect decreases the diameter of discharge channel and correspondingly increases the energy on unit area of cross section of discharge channel. It also activates the plasma oscillation during the discharge process. And these effects will change the traditional material removal pattern of EDM.

4 EXPERIMENTAL SETUP

To test the validity of theoretical analysis about the influences of high frequency electromagnetic field on discharge channel growth in micro EDM, the experimental study of micro EDM using high frequency pulse power supply is carried out. The wire electro discharge grinding (WEDG) module of self-developed micro EDM machine is used to fabricate a right square prism on micro electrode. The experimental equipment is shown in Fig. 4. Cylindrical electrode material is tungsten with the length of 100 mm and the diameter of 300 μm before machining. The dimension of the right square prism is 60 μm$\times$60 μm$\times$150 μm. The machining process is divided into roughing and finishing. In the finish machining, pulse on time T_{on} and pulse off time T_{off} are all set as 1 μs, then the discharge frequency is 500 kHz. The experimental conditions used in the finish machining are shown in Table 1. The tools after machining are observed with scanning electron microscope (SEM). The local part of obtained right square prism after micro EDM under high frequency discharge pulses is shown in Fig. 5.



(a) Three-axis CNC micro EDM machine

(b) WEDG module

Fig. 4 Experimental equipment

Table 1 Experimental conditions of micro EDM finish machining

Parameter	Description
Wire material	Brass
Tool material	Tungsten
Dielectric	Commonwealth 185
Voltage/V	70
Capacitance/pF	100
Polarity	Cathode: wire, Anode: electrode

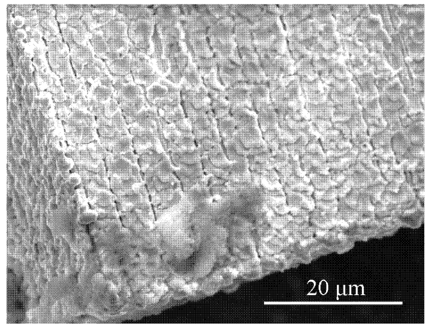


Fig. 5 SEM picture of obtained right square prism after micro EDM

5 EXPERIMENTAL RESULTS AND DISCUSSIONS

5.1 Measurement of discharge crater diameter

From the observation of discharge craters on the surface, the discharge craters are nearly irregular circles or ellipses. This is because of the perturbation of discharge channel during the discharge process, so that the minimum diameter of discharge crater is the one which directly relates to the diameter of discharge channel. The minimum diameter of discharge crater is shown in Fig. 6. For diameter measurement, 15 discharge craters on micro EDMed surface are randomly selected. The measured result of each crater diameter is shown in Fig. 7.

The average value of discharge crater mini-

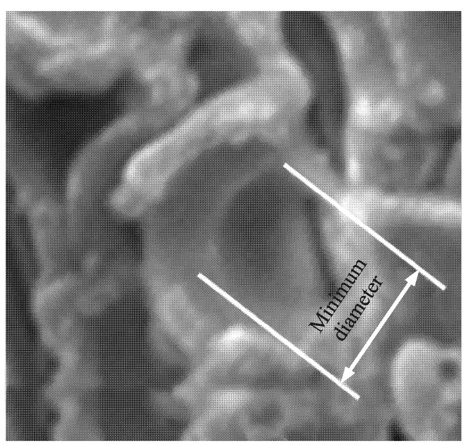


Fig. 6 Minimum diameter of discharge crater

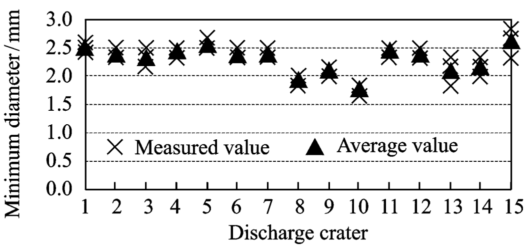


Fig. 7 Measured result of discharge crater minimum diameter

mum diameter is obtained as around 2.3 μm, thus the radius of discharge channel. For ease of calculation, $a=1.2$ μm is used as a condition of numerical calculation.

5.2 Electrode surface appearances under high frequency machining

The machined surface of electrode is shown in Fig. 8. It is clear that the discharge craters on the machined surface of electrode are narrow and deep; The shapes of discharge craters are irregular, and some of discharge craters are interconnected with each other; There exist many recast globules of debris with different volumes on the surface. These phenomena are unusual in low frequency EDM.

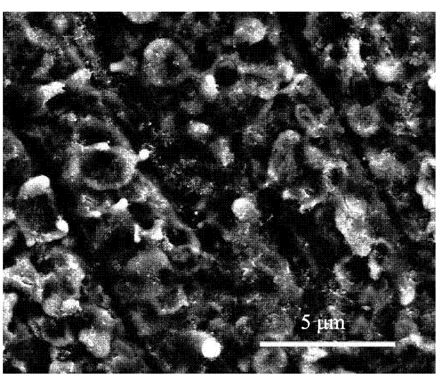


Fig. 8 Surface topography of machined electrode in micro EDM

Narrow and deep discharge craters correspond to the decrease of the discharge channel diameter and the increase of energy density, and this is the result that under the conditions of high frequency pulses, strong magnetic pinch effect limits plasma expansion. Additionally, longitudinal vibration is the reason for the deep discharge craters. The irregular shapes of the discharge craters indicate the moving center of the discharge channel during the discharge process, and this corresponds to the transverse vibration of plasma oscillation. The transverse vibration makes the location and residence time of plasma center change randomly. In the place of long residence time, the approximate discharge crater can be shaped, while in the place of short residence time, the transition zone between discharge craters is formed. This is the reason why there are some discharge craters with irregular shapes, different depths and the interconnection of some discharge craters, as shown in Fig. 8. It is because that the location and residence time of interface center between discharging channel and electrode surface change randomly according to the transverse vibration effect of plasma oscillation.

So many recast globules of debris indicate the intenseness of material removal process. In micro EDM, the recast debris globules of machined surface are not as homogeneous in all directions as that in conventional EDM (Fig. 9). In Fig. 9, $T_{on}=25$ μs, $T_{off}=25$ μs, and $I_m=6$ A. It seems that the molten materials are removed from one direction. This may because that the original interface center of discharge channel staggers a certain displacement to the side of plasma for the transverse vibration. The molten metal is immediately ejected out from the gap and then recasts at the edge of discharge crater. Fig. 10 indicates this material removal process. In Fig. 10, the left shows the electro thermal effect of discharge channel melts local electrode material. When the oscillation of plasma becomes acute, the location

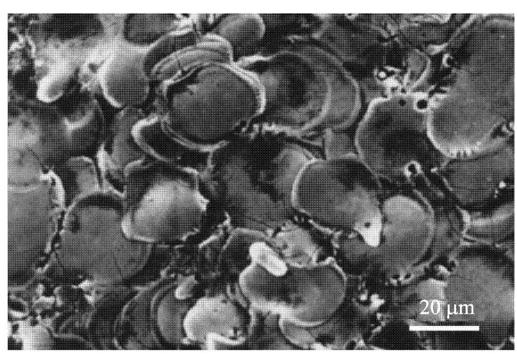


Fig. 9 Electrode surface topography after micro conventional EDM

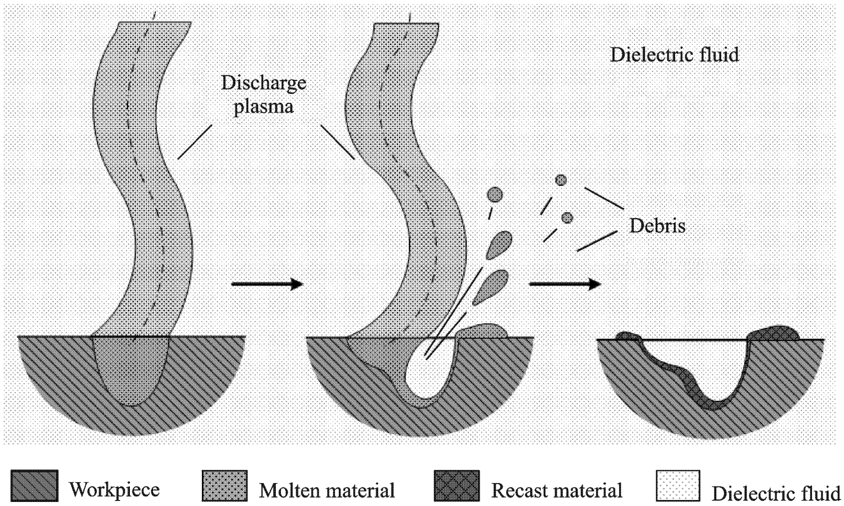


Fig. 10 Molten material removal process under effect of plasma transverse vibration

of discharging point changes, and the active area of plasma electro thermal effect changes correspondingly. The surface pressure of part molten materials, which once are under high pressure, drops sharply. The molten material is removed away laterad, as shown in the middle of Fig. 10. The right of Fig. 10 indicates the corresponding surface feature of discharge crater on electrode surface after this electrical discharge process. In Fig. 8, it is also easy to see that some of the recast globules of debris are very small, some are big, several of their diameters are even as large as those of discharge craters. The recast globules of debris with small volume may come from the alternating melting-removing process with less molten materials and less removing energy, while the large volume recast globules of debris might be formed from acute ejection from instantaneously acute ejection and then resolidification.

Through the analysis of special appearances on micro EDMed surface in the experiment results, it is concluded that micro EDM with high frequency pulse are intense processes. However, why the small discharge energy used in micro EDM can create more intense discharge process than conventional EDM? This may be because under the high frequency pulses, the strong magnetic pinch effect concentrates the discharge energy, though the total energy is small, it is able to produce higher energy density.

Under the effect of high frequency electromagnetic field, in the discharge process of micro EDM, the diameter decrease of discharge channel caused by strong magnetic pinch effect leads to the changes of discharge conditions such as energy density concentration of discharge plasma, and further, the intense oscillation of plasma. This is the importance reason that there appear special phenomena on the surface topography of discharge crater formation and distribution, molten material production and removal in micro EDM. Accordingly, it is considered that through the methods for reducing the frequency of discharge pulse, for instance increasing pulse off time, the material removal process in micro EDM can be improved.

6 CONCLUSIONS

The change of micro EDM process in high frequency electromagnetic field is one of the important reasons for the existence of differences between micro EDM and conventional EDM. According to the relationship between discharge channel and electrode surface appearance in electrical discharge, the influence of high frequency electromagnetic field on discharge channel expansion and configuration change is conducted, and further, the surface topography formation law is analyzed. Through the theoretical calculation and experimental study, some conclusions are obtained as follows:

(1) High frequency pulse increases the magnetic pinch effect of discharge channel significantly in micro EDM.

(2) Under strong magnetic pinch effect, the discharge channel diameter decreases, and the energy density of plasma particles in discharge channel increases remarkably.

(3) The thinner and stronger discharge channel and its oscillation effect are the important reasons for the special changes of electrode topography during micro EDM process.

References:

[1] Rajurkar K P, Levy G, Malshe A, et al. Micro and nano machining by electro-physical and chemical processes[J]. Annals of the CIRP, 2006,55(2):643-666.

[2] Rajurkar K P, Yu Zuyuan. 3D micro-EDM using CAD/CAM[J]. Annals of the CIRP, 2000,49(1):127-130.

[3] Masuzawa T. State of the art of micromachining[J]. Annals of the CIRP, 2000,49(2):473-488.

[4] Schacht B, Kruth J P, Lauwers B, et al. The skin-effect in ferromagnetic electrodes for wire-EDM[J]. International Journal of Advanced Manufacturing Technology, 2004,23:794-799.

[5] Pandey P C, Jilani S T. Plasma channel growth and the resolidified layer in EDM[J]. Precision Engineering, 1986,8(2):104-110.

[6] Li Minghui. Theoretical basis of electrical discharge machining[M]. Beijing: National Defense Industry Press, 1988. (in Chinese)

[7] Qi Liwei, Lou Leming, Li Minghui. Mechanism of electrical discharge machining and wave characteristics of plasma channel[J]. Journal of Shanghai Jiaotong University, 2001,35(7):989-992. (in Chinese)

[8] Schuster R, Kirchner V, Allongue P, et al. Electrochemical micromachining[J]. Science, 2000,289:98-101.

[9] Liberman M A, DeGroot J S, Toor A, et al. Physics of high-density z-pinch plasmas [M]. New York: Springer-Verlag, 1999.

[10] Huang Lizhen. Principle of electromagnetic field [M]. Beijing: People's Education Press, 1988. (in Chinese)

[11] Liu Yu, Zhao Fuling, Wang Yuangang, et al. Influences of skin-effect on micro-EDM[J]. Journal of Dalian University of Technology, 2010,50(3):362-367. (in Chinese)

高频脉冲微细电火花加工放电通道形成过程

刘 宇[1] 王 津[2] 王元刚[3] 赵福令[2]

(1. 大连交通大学机械工程学院,大连,116028,中国;

2. 大连理工大学精密与特种加工教育部重点实验室,大连,116024,中国;

3. 大连大学机械工程学院,大连,116622,中国)

摘要:研究了微细电火花加工中,高频电磁场形成的强磁力箍缩效应对加工过程中放电通道扩张及放电通道位形变化的影响。计算了高频电磁场作用下,放电通道中带电粒子所受洛伦兹力的变化情况。通过理论分析与实验研究,推测了放电通道的形成过程,认为在高频电磁场中,放电通道在强磁力箍缩效应作用下产生的通道直径减小、能量密度增大等变化是微细电火花加工表面出现的一系列特殊现象的重要原因。

关键词:微细电火花加工;放电通道;高频电磁场;磁力箍缩;放电凹坑

中图分类号:TG661

(Executive editor: Sun Jing)

基金项目:国家自然科学基金(50635040)资助项目。