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Design of a Magnetic Field Generator for Compression Plasma Discharge Channel of Micro EDM Deposition

Peng Zilong[1, 2*], Liu Yonghong[2], Li Yinan[1], Zhang Yiyao[1] and Wang Liping[3]

[1]School of Mechanical Engineering, Qingdao Technological University, Qingdao, 266033, China
[2]College of Electromechanical Engineering, China University of Petroleum, Qingdao, 266580, China
[3]School of Computer Science, Engineering and Mathematics, Flinders University, South Australia 5042, Australia

pzlmail@163.com

Abstract

A magnetic field generator for compression plasma discharge channel of micro EDM deposition has been designed. The self-magnetic field type by discharge current in the plasma channel of micro EDM deposition process has been analyzed. It presents a stable gradient annular magnetic field with the variables of discharge current and the distance from the discharge center. The force analysis of the charged particles in the discharge plasma channel under the self-magnetic field has been researched. The design principles of external magnetic field for enhancing the self-magnetic field to influence the machining performance have been put forward. Then, the structure type and dimension of external magnetic field generator have been determined. Results show that the external magnetic generator has the capability to enhance the self-magnetic field for compression plasma discharge channel with the proper structure parameters. With the increasing of the number of turns to 20, the external magnetic generator can influence the range of 0.10mm to 0.20mm from discharge channel center.

Keywords: *micro EDM deposition, discharge plasma channel, self-magnetic field, external magnetic field generator*

1. Introduction

Electrical discharge machining (EDM) as a successful and high machining accuracy method has been popular used in manufacturing industry for machining material of hard-to-cut. The feature of noncontact machining mode and the electro-thermal removal process made EDM method can afford to machine broad machining spectrum of materials including metal, semiconductor, and even insulating ceramic [1-3]. Especially, with the unique advantages, EDM has been become a forefront technology to overcome some knotty points in the fields referring to deep-small hole machining and low rigidity parts machining.

After nearly 70 years of development, with its inherent characteristics EDM technology has gradually become an important part of modern manufacturing. It transforms the discharge phenomenon from spark erosion of damage phenomenon to a processing method with high machining accuracy in many processing fields. With the fast development of discharge phenomenon, the application field of EDM has not been limited to the traditional die-sinking EDM in die and mode industry for material removal, but has developed a series of new process based on the further researches of discharge mechanism, machining medium, and

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machining strategy. The successful applications of powder mixed EDM, dry-EDM and near dry-EDM has been verified the importance of the function of machining medium [4-6]. With different type of machining medium, the EDM performance has noticeable differences. It has been break the cognition of EDM process can only be acted in kerosene or deionized water. Meanwhile, the processes of EDM surface modification and EDM deposition based on material deposition made people realize that the EDM process cannot be limited in traditional removal process.

It is well known that the discharge phenomenon of EDM has obvious influences on the EDM performance. The discharge mechanism of EDM including the discharge energy distribution, the micro process of material removal and migration in micro discharge distance between the tool electrode and the workpiece has been the research hotspots of EDM. Especially, rapid development of micro parts with the feature dimension of 0.1 mm to 1mm made EDM method have a widely application and have been a powerful micro manufacturing method. During traditional EDM, the discharge occurs between the tool electrode and worpiece under the pulse energy in a small distance less than several hundred microns.

With the feed movement of tool electrode, the shape of tool electrode will be copied to the workpiece accurately. The machinability of material in EDM has much to do with the melting or boiling point, regardless the material harness, which made EDM process have the strength in machining micro structures with hard metal materials. But in micro EDM, the discharge energy must to be reduced to the very low level about 10^{-7} Joule to ensure the micro material removal amount. The discharge gap and discharge area in micro EDM will be confined in a very small space, which causes a series of novel issues of discharge phenomenon different from the traditional EDM used high level discharge parameters. In micro EDM, the lower the discharge voltage is, the lesser the discharge distance between electrodes will be. The small discharge distance between electrodes will lead to the high level of tool electrode wear in the discharges, which will destroy the machining precision in micro EDM removal process.

Modern manufacturing needs the micro machining technology transform from two-dimensional planar structure to the complex three-dimensional structures in machining objects, from traditional silicon material to the superior performance alloy materials, traditional separation processing to a variety of processing methods of integrated processing. The research of new micro machining method for metal micro parts fabrication in the micro-nano scale with three-dimensional processing capacity becomes urgent increasingly. So, micro EDM process needs to do the corresponding development to meet the desired requirements of the modern machining. Many beneficial attempts of micro EDM have been carried out in the experimental and theoretical researches. Introducing external energy fields to influence the discharge course of micro EDM have been the research focus and many significant results have been reported.

The ultrasonic field and magnetic field are common external energy fields used in micro EDM process for improve discharge stability and EDM performance. Yu *et al.* [7] introduced the ultrasonic vibration in micro EDM process for drilling micro deep holes. The tool electrode was driven to do the planetary movement to improve the debris and bubbles out of the working areas. They reported micro holes have been obtained with the aspect ratio 29. Pay Jun Liew *et al.* [8] reported that when drill deep micro holes of ceramic materials, an ultrasonic vibration was applied to dielectric fluid. They believe that both the stirring effect and cloud cavitation effect were introduced to help the debris removal out of the discharge area.. Micro-holes with 10 μm in diameters and high aspect ratios (>20) were fabricated on reaction-bonded silicon carbide in a few minutes. Fu *et al.* [9] proposed a self-adaptive electrical discharge machining system. They reported that the new system can realize adaptive regulation of discharge gap depending, and help to achieve stable machining, high material removal rate, and good roundness of micro holes.

On the other hand, introducing magnetic field as external energy fields to influence the discharge channel in EDM process has been attract attention of people for improve EDM performance. Lin *et al.* [10] presented a magnetic force-assisted EDM process to help the expelling debris from the machining gap fast and easily and obtain the machining stability when machining SKD 61 steel using copper tool electrode. Reza Teimouri *et al.* [11] researched the rotary magnetic field-assisted dry EDM with ultrasonic vibration of workpiece. They believed that magnetic field has positive effects on the material removal rate and surface roughness. S. Joshi *et al.* [12] researched the hybrid process of dry EDM performed in a pulsating magnetic. They used a pulsating magnetic field applied tangential to the electric field to increase the movement of electrons in discharge plasma. They reported from experiments that the productivity improves 130% and tool wear can be ignored.

From the discharge mechanism of micro EDM process, the small discharge area will lead to the high level of tool electrode wear and more difficulty of machining debits removal out of the discharge area. Which is always deteriorated the machining stability of micro EDM for removal process. But last researches show that by controlling the discharge conditions, micro EDM in gas machining medium can achieve the deposition machining. That is to say micro EDM deposition can achieve the cumulative growth of tool electrode material on the workpiece surface to form micro structures [13]. As the stochastic nature of the discharge, it is hard to fully explain the mechanism of material migration in discharges. The micro EDM deposition process is a growth process, so the deposited material has the advantages of easy to be observed, it is more beneficial to research micro discharge mechanism of EDM process.

In this paper, a magnetic field generator for coaxial compression plasma discharge channel of micro EDM deposition has been designed. The plasma discharge channel type was analyzed and the self-magnetic field of discharge current used in micro EDM deposition calculated firstly. The particle motions in the discharge channel were researched, the equivalent force of motion particles under self-magnetic field and electrical field has been analyzed. Then the external magnetic field mode for coaxial compression plasma discharge channel has been determined. The external magnetic control parameters such as current, coin turns, magnetic generator structure dimension and so on has been optimized. The focus of this paper is to establish a space magnetic field for compression the discharge channel diameter, results of the discharge energy will be concentrated to increase discharge energy density for increase the material removal amount in one discharge. The novel external magnetic field type for coaxial compression plasma discharge channel has not been reported by former research, and is expect to increase the machining efficiency of micro EDM deposition process. As the principle of micro EDM deposition is the reverse machining course of micro EDM removal process, the research has an important significance for further understanding the micro discharge mechanism in micro EDM also.

2. Micro EDM Deposition Principles

2.1 Micro EDM Deposition Process

Micro EDM deposition is the reverse process of micro EDM removal process. The machining principle is followed the general rule of micro EDM. The discharge course can be also divided into the follow continuous steps. First, the open voltage is added onto the tool electrode and the workpiece and the tool electrode do the feeding motion towards workpiece under the gap condition control signal. When the gap distance between tool electrode and workpiece is so small that the gap electric field force increases extremely and exceeds the insulation strength of the dielectric, mass of electrons will be emitted from cathode surface under the action of the Joule heat and electric field force. Then the emitted electrons will be accelerated and moved to the anode under the electric field force between the anode and cathode. Tremendous collision will be occurred between high speed electrons and the dielectric medium particles, the plasma discharge channel with high temperature will be formed. Then the dielectric medium will be decomposed and the diameter of plasma channel will be expanded. In the discharge plasma channel, the extremely high temperatures made the materials of tool electrode and workpiece melt or gasify in a small amount. When the voltage drops, the pressure of plasma channel disappears and the melted or gasified materials from electrodes will removed from the discharge channel and one discharge finished. The EDM deposition and removal process has the similar discharge course. And the polarity effect and discharge condition is the main factors to decide the deposition process or removal process. The principle of micro EDM deposition sketch is shown Figure 1. It has been shown the micro EDM conditions and the micro process of discharge phenomenon in the discharge channel.

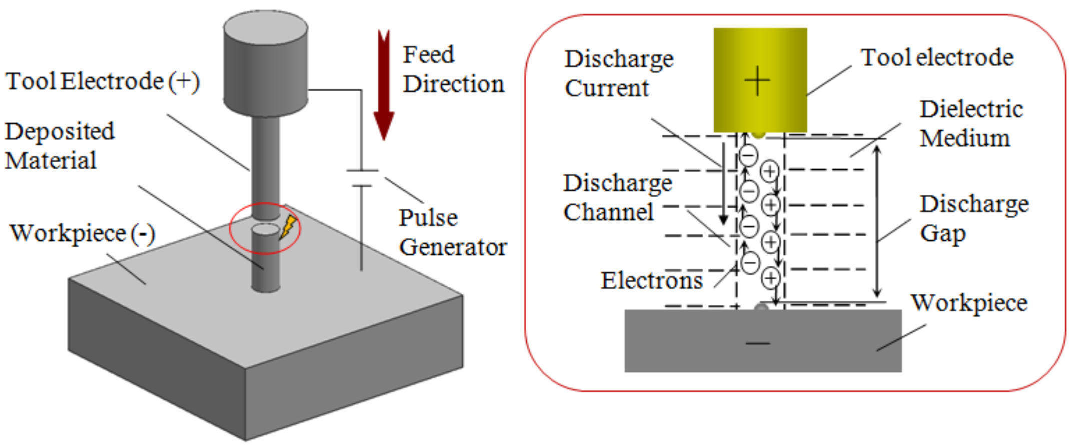

Figure 1. Principle of Micro EDM Deposition Sketch

From the discharge course of micro EDM process, it can be seen that materials both on tool electrodes and workpiece participated in discharge will be removed in a small amount in the discharge channel by the high temperature. The discharge will occur on the position where distance between tool electrode and workpiece is shortest. The directed motion of electrons and positive ions will form discharge plasma current in the small discharge gap with the level of several micron. It should be noticed that the diameter of the discharge plasma is not constant but expands with the discharge on-time. The more the discharge on-time is, the larger the plasma discharge diameter is. The plasma discharge channel is a time-varying quantity with the discharge on-time, which is usually defined as heat flux loaded diameter. From polarity effect of EDM that under the condition of small discharge on-time is applied, the removal amount of the anode is much larger than that of the cathode as the mass of electrons is much smaller than that of ions in discharge plasma. So in micro EDM deposition process, the tool electrode should be set as anode and workpiece was set as cathode to increase the tool electrode wear and reduce the deposited material removal under the discharge energy. Considering the fast cooling of removed material is harmful to the material deposition, the micro EDM deposition process should select gas medium, which is a key factor for micro EDM deposition process. In our former researches, the discharge condition has been determined. We can define the micro EDM deposition process that is a new EDM method, in which the two fundamental factors should be ensured. One is gas dielectric medium; the other is narrow discharge on-time and tool electrode setting as anode.

2.2 Self-Magnetic Field Type Analysis

It can be seen from the section of 2.1 that the directed motion of electrons and positive ions after the plasma discharged channel formation, will from a discharge plasma current in the small discharge gap. As the discharge gap about several microns is so small compared to the tool electrode that the discharge current on the discharge on-time can be made equivalent as an infinite long rectilinear wire. The self-magnetic field type around the discharge gap should be followed the right hand screw rule. And an annular gradient stable magnetic field will be generated around the discharge current. The self-magnetic field type of the discharge current after equivalent treatment was shown in Figure 2.

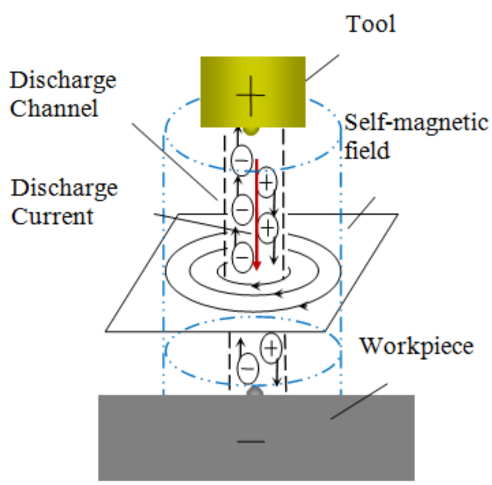

Figure 2. The Self-Magnetic Field Type of the Discharge Current

It can be seen that the self-magnetic field type generated by the discharge current presents a series of concentric circles with the gradient from the discharge current center to the infinity point, the small the distance apart from the discharge center is, the larger the self-magnetic field strength is. The plane involves the concentric circles of the self-magnetic field is vertical to the discharge channel.

2.3 Force Analysis of Charged Particles in the Discharge Channel

Now the Lorentz force of the motion charged particles in the discharge channel can be calculated under the formula

$$F = q\, V \times B \qquad (1)$$

Where, F is the Lorentz force of motion charged particles (N), q is the electric charge of particles (C), V is the velocity of motion charged particles (m/s), and B is the magnetic induction intensity (T).

In the plasma discharge channel, the direction of motion positive particles velocity is under the electric field direction, the direction of magnetic induction intensity is the tangent of the self-magnetic field concentric circle at the point. And the Lorentz force of motion charged particles in the self-magnetic field is the cross product of the vectors *V* and *B*. The direction of F is vertical to the plane of $V\times B$, and pointed to the discharge plasma channel center, as shown in Figure 3.

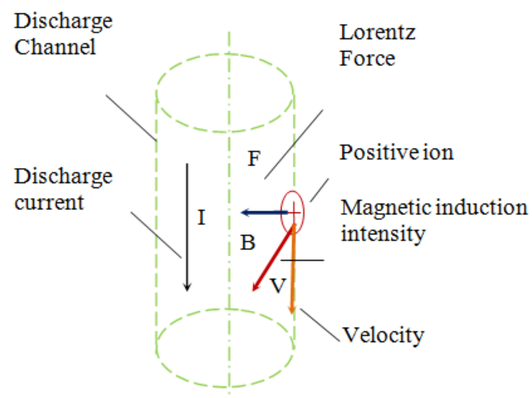

Figure 3. Force Analysis of Particle on the Edge of Discharge channel

In Figure 3, supposing a positive ion at the edge of the plasma discharge channel, the Lorentz force *F* is to point the discharge channel center, it will change the motion direction of the positive ion to move toward the discharge center. Similar, the motion of the electrons in the discharge channel has the same influence and will move toward the discharge center too. It is sure that the self-magnetic field has function of compressing the discharge channel expansion in discharge with the period of discharge on-time. As the micro EDM deposition process select gas as the working medium which the compression function to the discharge channel expansion is weak, the discharge channel expands rapidly in the radial direction. The discharge area will be enlarged and the discharge energy density will be dropped, it will decrease the machining efficiency.

3. Calculation of Self-Magnetic Field Intensity of Discharge Channel

The self-magnetic field strength is a function of the distance from the discharge current center. Considering the micro EDM deposition process need select the low discharge current, the discharge current has be selected 2.2A for the theoretical calculation. According to the magnetic field strength of an infinite long rectilinear wire with the current of 2.2A, the magnetic field strength around the discharge current can be expressed as followed.

$$\mathrm{B} = \frac{\mu_0 I}{2\pi R} \tag{2}$$

Where, B is the magnetic induction intensity (T), μ_0 is the permeability of vacuum with the value of $4\pi\times10^{-7}$ (T m A^{-1}), *I* is the discharge current with the value of 2.2A, *R* is the distance of the point to the discharge current center (m).

Under this condition, the magnetic induction intensity of self- magnetic can be express as a function of the variable *R*.

$$B= (4.4\times10^{-7}) /R \tag{3}$$

It can be seen that when the discharge current is selected as a constant, the self-magnetic induction intensity in micro EDM deposition only influence by the distance of the position to the discharge current center. In micro EDM deposition process, the discharge current is selected as 2.2A, and the diameter of tool electrode usually used less than 0.2mm, the minimum of the magnetic induction intensity is laid on the position of tool electrode edge because of the discharge point could not exceed the area of tool electrode.

Then the minimum of the self-magnetic induction intensity can be calculated as B_{min}= 2.2×10^{-3} (T). With the distance to the discharge center reduces, the self-magnetic induction intensity will enlarge with the inverse ratio of the distance of R.

4. External Magnetic Field Type for Compression of Discharge Channel

4.1 External Magnetic Design Principles

The purpose of this research is to introduce an external magnetic for compression the discharge channel to improve the discharge energy density as the radial direction of discharge plasma channel was restricted. So there are several principles should be followed.

The first, the external magnetic should accordance with the self-magnetic field direction. It will enhance the compression function of self-magnetic field to the discharge plasma channel. This principle is the design fundamental of the external magnetic generator.

The second, the external magnetic intensity should be large enough to influence the self-magnetic induction intensity in the small area of discharge channel with the diameter less than the micro tool electrode.

The third, the external magnetic structure should not have the path interference with the feeding motion of the tool electrode towards to workpiece in micro EDM deposition process.

Finally, the value of steady current should be not too large to superheat of the external magnetic structure to obtain the enough external magnetic intensity.

4.2 External Magnetic Generator Type

According to the design principles, the external magnetic generator has been determined, as shown in Figure 4. The magnetic generator adopts rectangle structure and distributes uniformly around the discharge current (machining area).

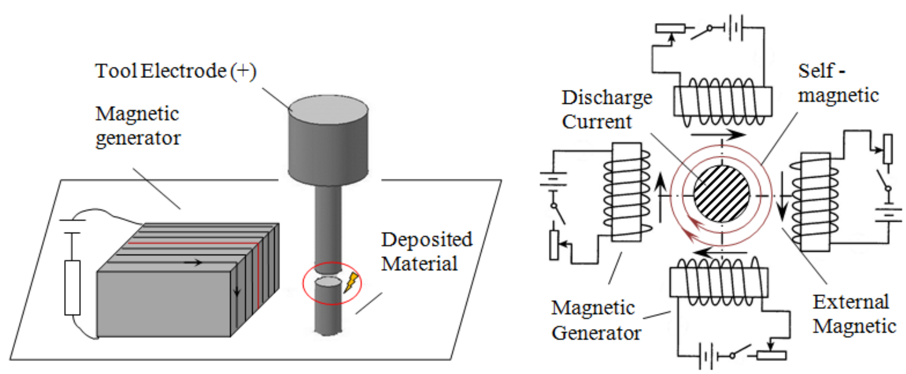

Figure 4 The External Magnetic Generator Type

The external magnetic generator framework selected non ferromagnetic materials to ensure the magnetic intensity out of solenoid field. The self-magnetic field of the discharge current in the discharge plasma channel is a clockwise annular gradient stable magnetic field. The external magnetic is the same type as the self-magnetic field according to the superposition principle of magnetic field.

It should be noticed that the external magnetic field also represents a gradient stable magnetic field, but the magnetic field intensity is reverse to the self-magnetic field. The nearer the distance to the discharge center is, the weaker the external magnetic field influence the discharge channel. So, it is necessary to ensure the enough external magnetic intensity to influence the small range of micro machining area in micro EDM deposition process. There are two major methods to enlarge the enough external magnetic intensity. One is to enlarge the current of external magnetic generator; the other is to enlarge the turns of the external magnetic generator. Obviously, increasing current will lead to heating the magnetic generator, and increasing turns will make the magnetic generator unwieldy.

4.3 External Magnetic Generator Structure Dimension

In order to determine the external magnetic generator structure dimension, the theoretical external magnetic intensity has been calculated using the Biot-Savart Law for the linear current per unit length in the space.

$$\mathrm{d}B = \frac{\mu_0}{4\pi} \cdot \frac{Idl \times r^0}{r^2} \tag{4}$$

Where, B is the magnetic induction intensity (T), μ_0 is the permeability of vacuum with the value of $4\pi\times10^{-7}$ (T m A^{-1}), I is the external magnetic generator current (A), dl is unit length of current element (m), r^0 is the unit vector of current element to the observation point, r is the distance of current element to the observation point (m).

Assuming that a single turn coil with rectangular, the length side is presented by L_1, L_2, L_3, and L_4 respectively as shown in Figure 4 presented by red color coin. Figure 5 shows the position of the single turn coil of external magnetic generator. The point P is the discharge point in micro EDM deposition process.

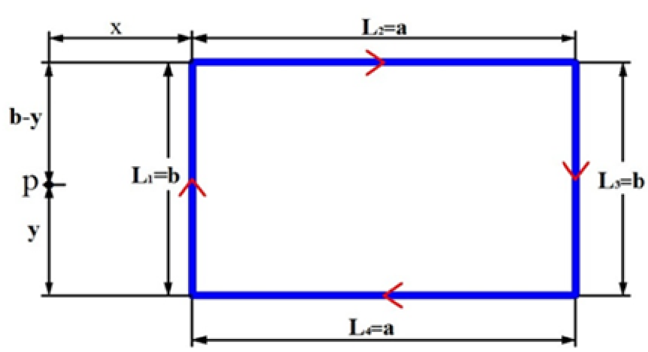

Figure 5. The Position of the Single Turn Coil of External Magnetic generator

With the positional relationship shown in Figure 5, we can see that the current flow past the route of L_1, L_2, L_3, and L_4 will influence the magnetic field of the point P, and the influence of the side of magnetic induction intensity can be calculated. Using the superposition principle of magnetic field influence of L_1, L_2, L_3, and L_4, the magnetic induction intensity of point P can be calculated. And the structure dimension of the parameter of b, a, x and y can be determined.

The magnetic induction intensity of the path L_1 to the point can be calculated by Biot-Savart Law as followed.

$$B_1 = \frac{\mu_0 I x}{4\pi}\int_{-y}^{b-y}\frac{dl_1}{(x^2+l^2)^{3/2}} = \frac{\mu_0 I}{4\pi}\cdot\frac{1}{x}\cdot\left(\frac{b-y}{(x^2+(b-y)^2)^{1/2}}+\frac{y}{(x^2+y^2)^{1/2}}\right) \tag{5}$$

The magnetic induction intensity of the path L_2 to the point can be calculated by Biot-Savart Law as followed.

$$B_2 = \frac{\mu_0 I(b-y)}{4\pi}\int_{x}^{x+a}\frac{dl_4}{((b-y)^2+(x+l_2)^2)^{3/2}} = \frac{\mu_0 I}{4\pi}\cdot\frac{1}{b-y}\cdot\left(\frac{a+2x}{((a+2x)^2+(b-y)^2)^{1/2}}-\frac{2x}{((2x)^2+(b-y)^2)^{1/2}}\right) \tag{6}$$

The magnetic induction intensity of the path L_3 to the point can be calculated by Biot-Savart Law as followed.

$$B_3 = \frac{\mu_0 I(a+x)}{4\pi}\int_{-y}^{b-y}\frac{dl_3}{((a+x)^2+l_3^2)^{3/2}} = \frac{\mu_0 I}{4\pi}\cdot\frac{1}{a+x}\cdot\left(\frac{b-y}{((a+x)^2+(b-y)^2)^{1/2}}+\frac{y}{((a+x)^2+y^2)^{1/2}}\right) \tag{7}$$

The magnetic induction intensity of the path L_4 to the point can be calculated by Biot-Savart Law as followed.

$$B_4 = \frac{\mu_0 I y}{4\pi}\int_{x}^{x+a}\frac{dl_4}{(y^2+(x+l_4)^2)^{1/2}} = \frac{\mu_0 I}{4\pi}\cdot\frac{1}{y}\cdot\left(\frac{a+2x}{((a+2x)^2+y^2))^{1/2}}-\frac{2x}{((2x)^2+y^2)^{1/2}}\right) \tag{8}$$

As the positional relationship of the sides of L_1, L_2, L_3, and L_4, the direction of magnetic induction intensity is different, so the total magnetic induction intensity can be expressed as followed.

$$B_{total} = B_1 + B_2 - B_3 - B_4 \tag{9}$$

Considering the practice experiments of micro EDM deposition process, we can enlarge the length to decrease the influence of B_3 to the point of P, which is to say that when the value of the distance L_2 is large enough, the influence of B_3 can be ignored. When the discharge point P is laid on the middle point of the length of b, as is b-y=b, influence of magnetic induction intensity by L_2 and L_4 to the point P is equal with value and reverse with direction, then B_2=B_4. So the B_{total} can be simplified as B_{total} =B_1.

Above all, the dimension of external magnetic generator structure can be determined with the length of b=0.02m, a=0.04m, x=0.01m, y=0.01m in single turn coin of magnetic generator structure.

Then

$$B_{total} = B_1 = 1.414\times10^{-5} I \text{ (T)} \tag{10}$$

Where, the parameter I is the steady current of external magnetic generator (A).

Considering the external magnetic field generator will be superheated in experiments, the maximum of steady current cannot be larger than that of the value 15A when using the 1.5 square millimeter conductor wire with the diameter about 1.37mm, so the B_{total} will reach

2.1×10^{-4} (T).

As former calculation results of the self-magnetic induction intensity, B_{min} at the point from the discharge center of 0.2mm is $B_{min}=2.2\times10^{-3}$ (T), so the external magnetic generator with single turn coin with $B_{total}=2.1\times10^{-4}$ (T) is not enough to influence of the self-magnetic induction intensity.

With the limitation of steady current lower than 15A, there are two parameters of external magnetic generator can be adjusted to enlarge the external magnetic induction intensity. One is the distance of magnetic generator side L_1 to the discharge center, the other is the number of turns of the external magnetic generator. Obviously, the former method will lead to the smaller operation space, so the latter method will be a good solution to enhance the external magnetic induction intensity.

Finally, when the number of turns of the external magnetic generator is increased to 20, the external magnetic induction intensity will reach 4.2×10^{-3} T at the point of discharge center. The influence range is 0.10mm to 0.20mm of discharge channel.

5. Conclusions

In this paper, a magnetic field generator for compression plasma discharge channel of micro EDM deposition has been designed. The external magnetic field type and the key parameters of magnetic generator for enhancement the self-magnetic field of discharge current has been determined. And the following conclusions have been drawn.

(1) The self-magnetic field type by discharge current in the plasma channel of micro EDM deposition process has been analyzed. The force analysis of charged particles in the discharge channel has been researched.

(2) The design principles of external magnetic for enhancement the self-magnetic field to influence the machining performance have been put forward. And the feasibility of external magnetic field generator type has been analyzed.

(3) The key parameters of magnetic generator for enhancement the self- magnetic field of discharge current has been determined. The influence range is 0.10mm to 0.20mm of discharge channel center. It is shown that the magnetic generator can enhance the self-magnetic field for compressing the discharge plasma channel

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Authors

Peng Zilong

He received his PhD degree in Mechanical Engineering (2010) from Harbin Institute of Technology, China. Now he is associate professor of School of Mechanical Engineering, Qingdao Technological University, China. 2011-2013, he is engaged in postdoctoral research in China University of Petroleum. His current research interests include non-traditional machining, micro machining, and EDM mechanism under coupled field and so on.

Liu Yonghong

He received his PhD degree in Mechanical Manufacture (1996) from Harbin Institute of Technology, China, Currently; he is a professor and doctoral supervisor in College of Electromechanical Engineering, China University of Petroleum. His research fields include electrical discharge machining; engineering ceramics compound machining, control system of subsea drilling equipments and so on.

Wang LiPing

She received the M. Eng. degree in mechanical engineering (2005) from Tianjin University, Tianjin, China. She is an associate professor in Shanghai Jianqiao University, China. Now, she is currently working towards the Ph.D. degree in School of Computer Science, Engineering and Mathematics, Flinders University, Australia. Her research interests include mechanical design, reverse engineering and biomechanics and biomaterials.