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Micro EDM deposition in air by single discharge thermo simulation

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Abstract: A thermo-physical model for micro electric discharge machining deposition process using finite element method (FEM) was introduced. The numerical analysis of the single spark operation of the process was carried out in FEM software ANSYS, considering the Gaussian distribution of heat flux, initial and boundary conditions, and energy distribution of different kinds of tool electrode and workpiece in material. The suitable discharge conditions for the deposition process were predicted from the transient temperature analysis. According to the results from the simulation analysis, a brass micro cylinder with approximately 200 μm in diameter and 1.2 mm in height was deposited on a steel surface, and the deposited material was close packed. The validity of the thermo-physical model and FEM solving procedure were proven through a lot of machining experiments and tests of the deposited material characters.

Key words: micro EDM deposition; thermo-physical model; FEM; single discharge; micro deposited cylinder

1 Introduction

In recent years, manufacturing industry has witnessed a rapid increase in demand for micro-products and miniaturized systems/components in many industrial sectors including the electronics, communications, medicine, automotive, and avionics industries [1−5]. Among the micromachining technologies, micro electrical discharge machining (micro-EDM) offers distinct advantages such as no direct mechanical contact, regardless of the materials hardness, able to machine 3D micro structures and further be extended by combining other micromachining methods to form hybrid processes, and has become an important issue in fabrication of small quantities micro-mould or micro-parts [5−6]. Because of the stochastic nature of the sparking, it is difficult to fully explain the mechanism of transient material removal in EDM. It has been known that the mechanism of material removal in EDM is based on electrical energy transfer and thermal process [7−9]. However, the phenomenon of the tool electrode wear caused by the sparking is inevitable and influences the machining accuracy, particularly in micro-EDM using small energy (<100 μJ). On the other hand, by making use of the tool wear, the EDM process can also be used as a surface treatment method and/or an additive process. A micro EDM deposition process, using tool electrode materials deposited on workpiece surface to fabricate the micro structures in EDM, was reported firstly by HAYAKAWA et al [10], the scholars of Japan Nagoya Institute of Technology. In the works, suitable discharge conditions for this process were predicted from the transient temperature analysis using uniform heat flux on the same materials of tool and workpiece, and a steel cylinder with 0.14 mm in diameter, 2.2 mm in height deposited on steel surface by using steel electrode with 0.1 mm in diameter [10]. ORI et al [11] realized an advanced alloying process using electrode cemented with two different materials by micro EDM deposition. JIN et al [12−13] investigated effects of discharge parameters on deposition process through a lot of machining experiments, and the results of experiments showed that wire tool electrode of diverse materials, brass, tungsten and steel can deposit on steel workpiece surface. PENG et al [14−15] researched the micro EDM deposition process and the fine texture of the deposited material, and fabricated micro structures by reversible electrical

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discharge machining method, which combines micro EDM deposition and micro selective removal on the same EDM machine tool.

According to previous researches in micro EDM deposition, it was found that the process theoretical research was relatively lagging behind its process method in practices. The mechanism of micro EDM deposition depends on electrical energy transfer and thermal process. This paper focuses on the establishment of the thermo-physical model in single discharge and its FEM solving procedure, and attempts to predict the suitable discharge conditions for the deposition process from the transient temperature analysis. Then a lot of machining experiments adopting predicted parameters and tests of the deposited material characters are introduced to validate the thermo-physical model and FEM solving procedure for micro EDM deposition process.

2 Temperature field analysis of tool and workpiece in micro EDM deposition

2.1 Thermo-physical models

For the transient, non-linear thermal analysis of the tool/workpiece in a single discharge EDM process, with the three assumptions that EDM spark channel is considered a uniform cylindrical column, heat transfer is mainly by conduction and convection, and radiation heat losses are neglected, a Fourier heat conduction equation is taken as the governing equation:

$$c\rho\frac{\partial T}{\partial t}=\lambda\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right) \tag{1}$$

where r and z are the coordinates of cylindrical work domain; T is temperature; ρ, c, λ and t are mass density, specific heat capacity, thermal conductivity and time, respectively. The initial and boundary conditions are described in Fig. 1.

Initial temperatures of tool electrode and workpiece are assumed to be uniform at environment temperature, T=T_0=298 K. A Gaussian distribution of heat flux input as the heat convection mode is used between the electrodes and the air. It is expressed by

$$q(r)=q_{\mathrm{m}}\exp(-kr^2)=h_{\mathrm{c}}(T_{\mathrm{s}}-T_0) \tag{2}$$

where $q(r)$ is the surface heat flux density at the position of radius r and depends on discharge parameters; q_{m} is the maximum heat flux density; k is the heat concentration factor; h_{c} is the heat convection coefficient; and T_{s} is the temperature of electrode surface.

These ratios of the energy distribution in the tool electrode and workpiece to the total discharge energy greatly depend on the polarity and the material of the tool and workpiece. XIA et al [16] reported that the energy distributed to anode is always greater than that to cathode, and the energy distribution to anode and cathode is about 40% and 25% respectively when copper was used for both anode and cathode. In our model, the energy distribution to anode of 50% and cathode of 20% was adopted when brass was used as anode and steel as cathode.

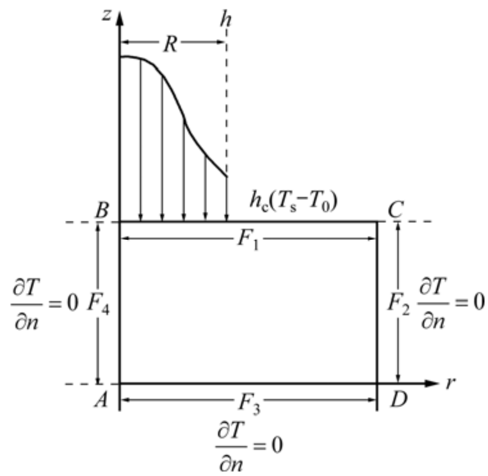

Fig. 1 Initial and boundary conditions of model

2.2 Temperature FEM simulation

In the analysis, a tool electrode with 0.2 mm in diameter and a single pulse discharge with pulse current of 1.5 A and pulse duration of 5 μs are ignited at the center of the discharging surface. The established thermo-physical micro EDM deposition model was introduced in the FEM software ANSYS. The temperature field distribution of the tool electrode and workpiece is shown in Fig. 2. Then, the temperature of the discharging spot with the variable of pulse duration of the tool electrode was obtained, as shown in Fig. 3. From identified four phase translation points A, B, C, and D, the T_{m} and T_{b} indicating melting point line and boiling point line of the tool electrode material were obtained respectively.

2.3 Prediction of micro EDM deposition conditions

Plotting the time required to reach points A and D versus the discharge current illustrates the limits of the machining conditions under which the electrode (anode) melts, indicated by dashed lines in Fig. 4. Similarly, the curve of the time versus discharge current for boiling limit was indicated by solid lines. In the same way, these

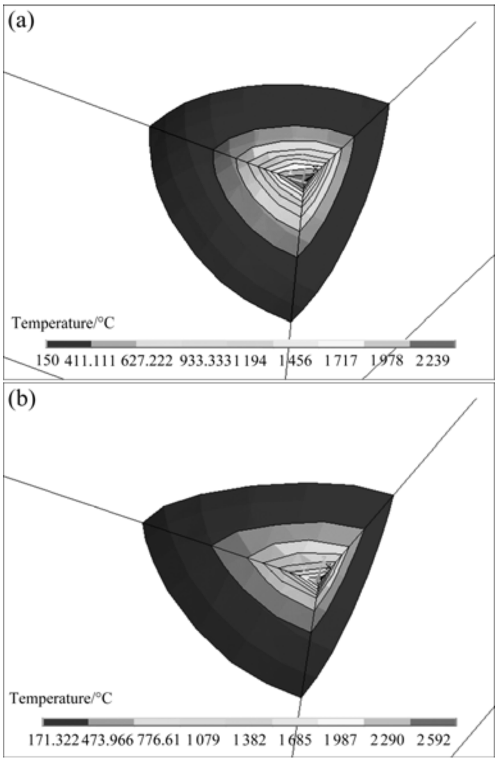

Fig. 2 Temperature field of single pulse discharge: (a) Brass as tool (anode); (b) Steel as workpiece (cathode)

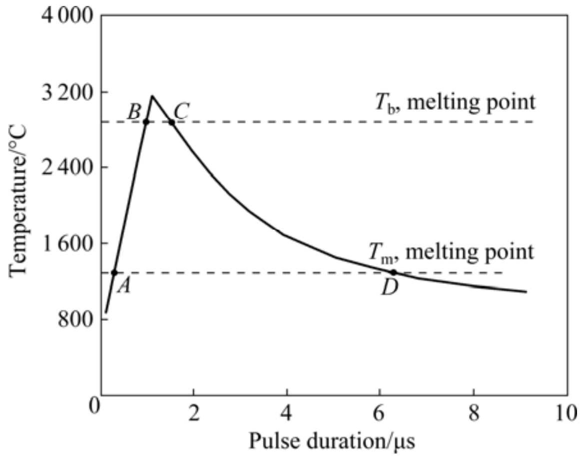

Fig. 3 Calculated temperature in discharge center of electrode with time at I=1.5 A

curves of the time versus discharge current for melting and boiling of workpiece (cathode) material were also obtained. The hatched domain shows the suitable discharge conditions of the deposition [4].

Accordingly, if the discharge current and duration are chosen within the hatched domain, the temperature of the anode exceeds the boiling point, and the temperature of cathode is between the melting point and boiling point, and the boiled anode material will deposit on the melted surface of the cathode.

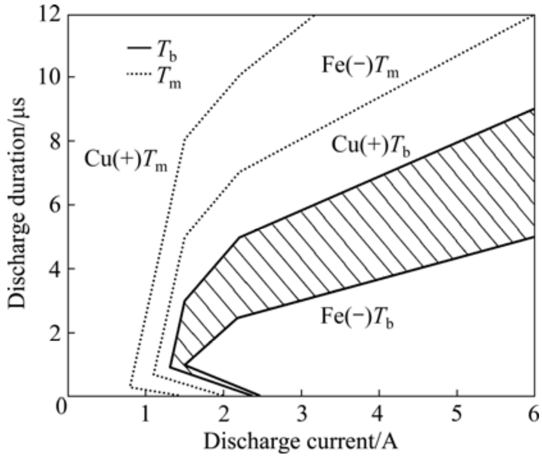

Fig. 4 Processing parameter range of micro EDM deposition in gas

3 Verification and test through experiments

3.1 Verification experiments

The experiments were carried out on a self-developed micro EDM machine. Brass electrode (d 0.2 mm) as tool electrode was connected with the anode, while high-speed steel as workpiece was connected with the cathode. In the machining course, through the z-axis servo feed movement, the tool electrode moves towards the workpiece. When the distance between two electrodes reaches the discharging gap, the deposition process can be realized. The three groups of experiments parameters, described in Table 1, were chosen to verify the obtained thermo-physical model and results of FEM simulation, and micro cylinder structure was deposited in each one of the three groups of experiments. There were a brass micro deposited cylinder and an electrode used in the deposition process, as shown in Fig. 5. The brass micro cylinder with about 200 μm in diameter and 1.2 mm in height was deposited on a steel surface under the condition of 4.3 A. The deposition process was stable and repetitive.

Table 1 Processing conditions of micro EDM deposition

Processing parameter	Value
Tool electrode	Brass
Workpiece	High-speed steel
Polarity	Electrode (+)
Working medium	Air
Open-circuit voltage/V	100
Discharge current, I_i/A	2.2, 4.3, 6.0
Discharge duration, t_i/μs	2, 4, 8
Pulse interval, t/μs	120, 120, 150
Deposition time, t_0/min	120, 120, 120

3.2 Characters test of deposited material

A lot of test methods were introduced to analyze the characters of the deposited materials: including scanning electron microscopy (SEM) analysis for diversified sections of deposited cylinder, line scanning energy spectrum of deposited interface, and energy spectrum analysis on the longitudinal profile of the deposited material. From SEM images (Fig. 6) of the cross section of deposited cylinder, and longitudinal section of top, middle and interface of the same cylinder, it was found

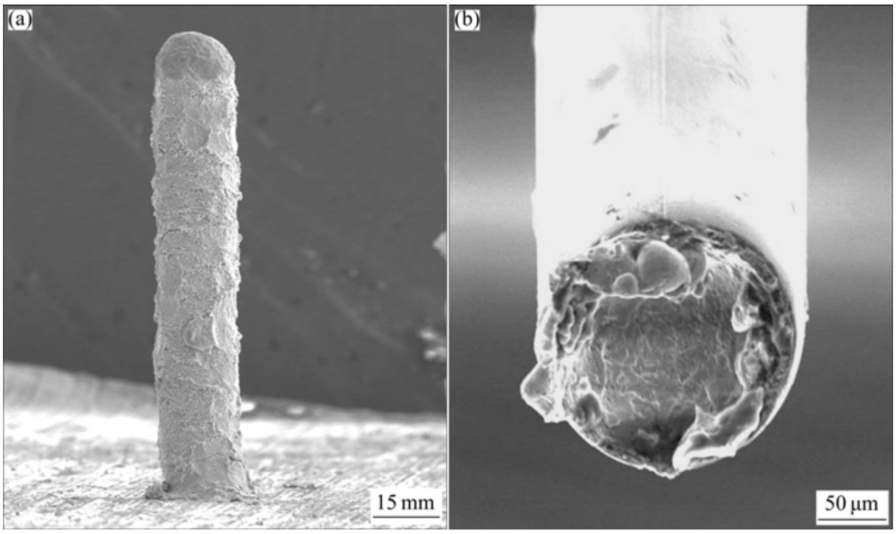

Fig. 5 Brass micro deposited cylinder and electrode used in deposition: (a) Cylinder deposition; (b) Electrode

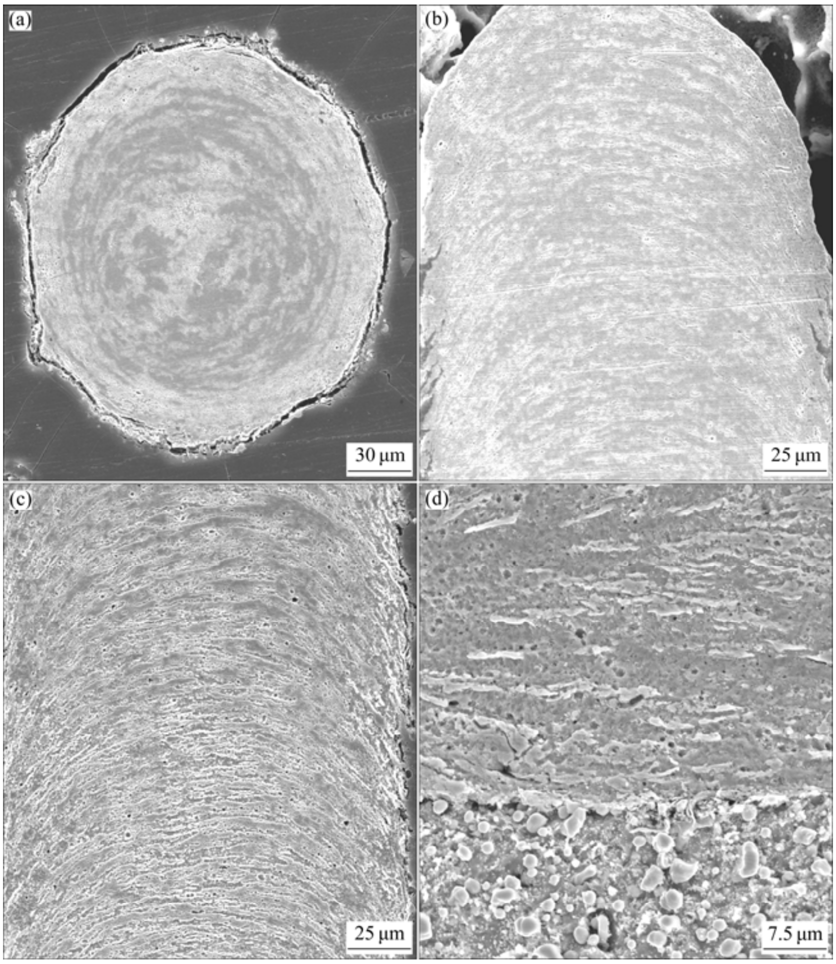

Fig. 6 SEM images of sections of deposited cylinder: (a) Cross section; (b) Longitudinal section of top; (c) Longitudinal section of middle; (d) Longitudinal section of interface

that the deposited material was close packed.

A line scanning energy spectrum analysis was applied to the interface between the deposited material and the workpiece, and the result is shown in Fig.7.

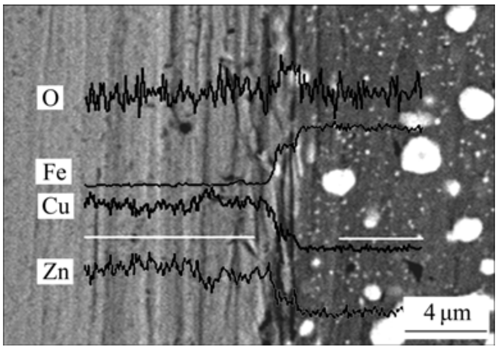

Fig. 7 Line scanning energy spectrum of deposited interface

In Fig. 7 the left part is the deposited material and the right part is the workpiece material. At the bonding interface, with Fe element mass fraction increasing, the mass fraction of Cu and Zn elements drops. The three elements coexist at the interface whose composition depends on the elements of the tool electrode and the base together. This bonding feature is generally considered the metallurgical bonging.

The result of the energy spectrum analysis on the longitudinal profile of the deposited material is shown in Fig. 8. It can be seen that the deposited material components are mainly Cu and Zn, which are almost the same as those of the brass tool electrode. A little amount of O element is found in the results. The mass fraction of O element is about 0.72%. It means that micro oxidation occurs in deposition with air medium.

These characters obtained from mentioned above tests further demonstrated that the machining parameters predicted by the thermo-physical FEM simulation are suitable for micro EDM deposition process.

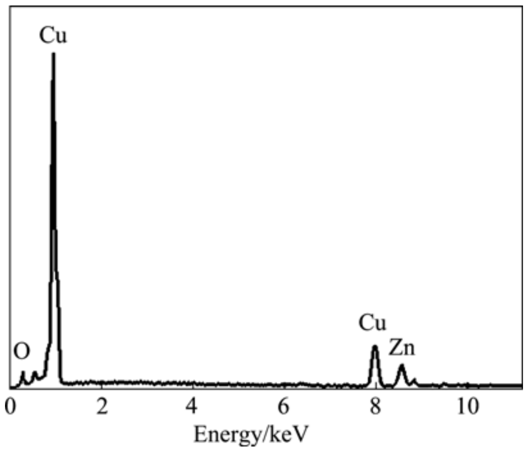

Fig. 8 Energy spectrum analysis on longitudinal profile

4 Conclusions

1) A thermo-physical model in single discharge for micro EDM deposition process was presented. The model was considered the Gaussian distribution of heat flux, initial and boundary conditions, and energy distribution of the polarity.

2) The suitable discharge conditions for the deposition process were predicted from the transient temperature analysis. According to the prediction, a brass micro cylinder with about 200 μm in diameter and 1.2 mm in height was deposited on a steel surface.

3) These characters obtained from deposited materials tests further demonstrated that the prediction by the thermo-physical FEM simulation is efficient.

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气中微细电火花沉积加工的单脉冲放电过程热力学仿真

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摘 要：建立气中微细电火花沉积加工过程电极材料的热物理模型。利用有限元分析软件 ANSYS 对单脉冲条件下的工具电极和工件的瞬态温度场进行数值模拟，分析热源形式、初始边界条件和放电能量分配对工具电极和工件材料蚀除形式的影响，并预测适合微细电火花沉积加工的工艺参数。采用仿真预测得到的工艺参数，在高速钢工具表面稳定沉积出直径约 200 μm、高度约 1.2 mm 的微圆柱结构。对沉积材料微观组织结构的测试分析表明，沉积材料与基体结合紧密。工艺实验和测试分析证明了所建立的微细电火花沉积加工过程的单脉冲放电热物理模型和有限元求解过程的正确性。

关键词：微细电火花沉积；热物理模型；有限元；单脉冲放电；微圆柱沉积

(Edited by YANG Hua)