International Journal of Heat and Mass Transfer 75 (2014) 425–432

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A novel method of determining energy distribution and plasma diameter of EDM

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ARTICLE INFO

Article history:
Received 24 June 2012
Received in revised form 3 January 2014
Accepted 31 March 2014

Keywords:
Electro discharge machining (EDM)
Energy distribution
Plasma diameter
Finite element method (FEM)
Crater

ABSTRACT

This work proposed a novel method of determining the energy distribution and plasma diameter of EDM. The energy distribution and plasma diameter were determined by comparing the boundary of the melted material in the crater which was obtained by metallographic method and the isothermal curve of the thermal-physical model using finite element method (FEM). The results of this work indicated that the expansion of the plasma diameter must be taken into consideration in order to be more consistent with the actual EDM process. With this method, the energy distribution and plasma diameter in different dielectrics with different polarities were investigated. Comparison between the results of this work and the previously reports showed that the energy distributed into workpiece and plasma diameter can be determined by this new method.

1. Introduction

Electrical discharge machining (EDM) is a widely used manufacturing method in the industry application. The electric conductive or semi-conductive [1,2] can be machined by this non-contact method regardless of their hardness. Almost seventy years passed since the innovation of the of EDM technology, however investigations are still going on to further improve the performance of this process by clarify the basic physical processes involved during the process. The EDM process was generally accepted as a thermal erosion process where heat transfer takes place. A number of simplified thermo-mathematical models based on the equations of heat conduction have been proposed to simulate the thermal process [3–7]. Review of the literatures showed that many researchers have estimated or predicted the material removal rate [4,8,9] (erosion of workpiece per unit time), residual thermal stress [9–11] thickness of the recast layer and surface roughness [12] based on the thermo-mathematical models.

The energy supplied into the discharge was converted into heat energy and was mainly distributed between the workpiece, tool electrode and dielectric. The energy was consumed by a number of physical processes, such as ignition, conduction, radiation, melting, evaporation and explosion. The energy distributed into workpiece was usually thought to be an important factor that affects the EDM performance [5,13]. Besides the energy distribution, the plasma diameter was another important factor. Investigation carried out by Zahiruddin and Kunieda [14] showed that the power density, which dependent on the discharge energy and plasma diameter, can significantly affect the energy and removal efficiencies of EDM. Therefore, precisely determination of the energy distributed ratio into the workpiece and plasma diameter will provide critical and insightful information for further understanding the basic physical process of EDM and enhance its application capacity.

As early as 1975, the energy distribution had been measured by Koenig et al. [15]. By measuring the temperatures of the electrodes and dielectric fluid. Xia et al. [16] and Hayakawa et al. [17] measured the energy distribution by comparing the measured temperatures of the electrodes with the calculated results obtained under the assumed ratio of the energy distributed in electrodes. Firstly, the temperature rise in the Cu electrode was measured by a thermocouple; then the temperature rise in the electrode was also calculated by thermal conduction model by assuming an energy distribution ratio into the electrode. The calculated will be repeated until the measured temperature coincide with the calculated temperature, and the assumed ratio was thought to be the ratio of energy that lost into the electrode due to conduction with regard to the total discharge energy. This method was also adopted in some recently investigations [14,18–20]. Singh [19] and Singh and Shukla [20] studied the energy distribution ratio into tungsten-carbide electrodes with this method. Zahiruddin and Kunieda [14,18] studied the energy distribution ratio of micro EDM. Generally, the thermocouple was fixed with a distance from the

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.03.082
0017-9310/

discharge point and the temperature rise signal was detected several millisecond after the discharge to avoid the electromagnetic noise. The measurement accuracy was greatly depended on the detected location of the thermocouple, geometry of the electrodes and capacity of resisting electromagnetic noise of the equipment. Therefore, it very difficult to precisely detect the energy distributed into the electrode by this method.

Precisely measurement of the plasma diameter was very difficult since the discharge occurred in such a narrow place and lasted for a very short time. High-speed video camera was used by Natsu et al. [21] to determine the diameter of the arc plasma. However, the light-emitting region photographed on camera may not be the arc plasma area where discharge current flows, and that the photographed diameter depends on camera settings such as exposure time and aperture of diaphragm. Therefore, the arc plasma diameter cannot be correctly measured by the high-speed video camera. Kojima et al. [22] who determined the diameter of the plasma by spectroscopic technique. They found that the arc plasma completes expanding within a few microseconds after dielectric breakdown while the diameter of craters grows slowly in comparison with the expanding speed of the arc plasma. Their finding is different from conventional plasma expansion models established based on the observation of generated craters.

This paper proposed a new method of determining the energy distribution and plasma diameter by comparing the boundary of the melted material in the crater which was obtained by metallographic method and the isothermal surface of the thermal-physical model using finite element method (FEM). Similar with the traditional method [16–20], first the boundary of the melted material which re-solidified in the crater were determined by metallographic method; then the boundary of the melted material was calculated by the thermal-physical model using finite element method by assuming an energy distributed ratio into workpiece and plasma diameter (i.e. heat flux diameter). The calculation will be repeated until the calculated boundary coincides with the measured.

2. Energy distribution model of EDM

2.1. Principle

During the EDM process, material was removed from both tool electrode and workpiece. In our case, only the workpiece will be investigated for simplicity. Fig. 1 illustrates the energy distribution into workpiece. X is the ratio of energy distributed into the workpiece with regard to the total discharge energy. A little fraction of X was carried away by debris and the remainder larger fraction was lost due to heat conduction [17,18]. In Fig. 1(a), X_{deb} and X_{con} are the ratio of energy carried away by debris and ratio of energy lost due to heat conduction within the workpiece with regard to the total discharge energy.

$$X = X_{con} + X_{deb} \quad (1)$$

The ratio of energy carried away by debris, X_{deb}, was calculated according to the thermal property of the workpiece material and volume of debris, V, which was experimentally determined by the metallographic method.

$$X_{deb} = \frac{E_{debm} + E_{debv}}{i_e u_e t_e} \quad (2)$$

$$V = V_m + V_v \quad (3)$$

where E_{debm} and E_{debv} is the amount of energy carried away by debris when the material removal is due to melting and vaporization, respectively. V_m and V_v is the volume of debris removed by melting and vaporization, respectively. i_e, u_e and t_e is the discharge current, discharge voltage and discharge time, respectively. In the following, the discharge time was referred as pulse duration since the breakdown delay was very short in our experiments.

$$E_{debm} = \rho V_m [c(T_{mv} - T_s) + L_m] \quad (4)$$

$$E_{debv} = \rho V_v [c(T_v - T_s) + L_m + L_v] \quad (5)$$

where ρ is the density [kg/m^3], c is the specific heat [J/(kg K)], T_{mv} is the temperature between melting and boiling point, T_v is the boiling point, T_s is the average temperature of the workpiece before the single discharge, L_m is the heat of fusion [J/kg], L_v is the evaporation heat [J/kg].

The removal efficiency, η, was defined as the ratio of debris volume, V, regarding to the total melted volume, V_s.

$$\eta = \frac{V}{V_s} \quad (6)$$

2.2. Heat conduction analysis

Fig. 2 shows flowchart of the analysis. Energy distributed into workpiece was carried away by debris and lost due to conduction as explained in Section 2.1. In this work the energy carried away by debris is calculated using the method proposed by Zahiruddin and Kunieda [14] by assuming a coefficient, g, as follow:

$$g = \frac{V_v}{V} \quad (7)$$

$g = 0$ means all the debris was removed by melting whereas $g = 1$ means all the debris was removed by evaporation.

The value of X_{con} was unknown. In principle, the unknown X_{con} is first assumed to be between 0 and 1 and multiplied with the total discharge energy obtained by the waveform recorded by oscilloscope to calculate the energy conducted into the workpiece. In this case, plasma diameter, R_{pc}, is another necessary parameters to calculate the power density at the workpiece surface. Similar with the case of X_{con}, the value of R_{pc} was assumed to be between 0 and R_{max}. The value of R_{max} was set as 1 mm based on the results reported by Kojima et al. [22]. During the calculation, the step size of X_{con} and R_{pc} was taken as 0.1% and 5 μm, respectively. Just as shown in Fig. 2, the value of X_{con} and R_{pc} was determined by comparing the measured and the simulated boundary of the melted material. The whole geometry parameters of the crater, including the diameter of melted material, d_{melt}, depth of melted material, h_{melt}, and volume of melted material, V_s, were compared. It was taken as coincidence when the difference between measured and simulated values of all of the three parameters is smaller than 3%. In Zahiruddin and Kunieda's study [14], only the diameter of crater was compared.

The generally accepted Fourier heat conduction equation was used as the governing equation.

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial R} + \frac{\partial^2 T}{\partial Z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (8)$$

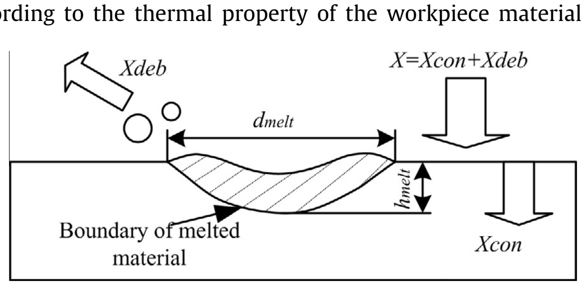

Fig. 1. Illustration of the discharge energy distributed into workpiece.