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Scale Effects and a Method for Similarity Evaluation in Micro Electrical Discharge Machining

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Abstract: Electrical discharge machining(EDM) is a promising non-traditional micro machining technology that offers a vast array of applications in the manufacturing industry. However, scale effects occur when machining at the micro-scale, which can make it difficult to predict and optimize the machining performances of micro EDM. A new concept of "scale effects" in micro EDM is proposed, the scale effects can reveal the difference in machining performances between micro EDM and conventional macro EDM. Similarity theory is presented to evaluate the scale effects in micro EDM. Single factor experiments are conducted and the experimental results are analyzed by discussing the similarity difference and similarity precision. The results show that the output results of scale effects in micro EDM do not change linearly with discharge parameters. The values of similarity precision of machining time significantly increase when scaling-down the capacitance or open-circuit voltage. It is indicated that the lower the scale of the discharge parameter, the greater the deviation of non-geometrical similarity degree over geometrical similarity degree, which means that the micro EDM system with lower discharge energy experiences more scale effects. The largest similarity difference is 5.34 while the largest similarity precision can be as high as 114.03. It is suggested that the similarity precision is more effective in reflecting the scale effects and their fluctuation than similarity difference. Consequently, similarity theory is suitable for evaluating the scale effects in micro EDM. This proposed research offers engineering values for optimizing the machining parameters and improving the machining performances of micro EDM.

Keywords: Electrical Discharge Machining (EDM), micro EDM, Scale effect, Similarity theory, Similarity evaluating method

1 Introduction

Electrical discharge machining(EDM) has been widely used in the manufacturing industry, particularly for difficult-to-cut materials, due to its contactless, electro-thermal material removal mechanism[1–2]. During each electrical discharge, the dielectric between the workpiece and tool electrode is broken down, which forms a plasma tunnel. This plasma is extended and the resulting high temperature causes melting and vaporization of the electrodes, whereupon the molten material is ejected when the plasma collapse, as shown in Fig. 1. After deionization, the dielectric between the electrodes is prepared for next discharge. As a result, with the tool feeding, the desired material is removed from the workpiece by a series of such discharge sparks.

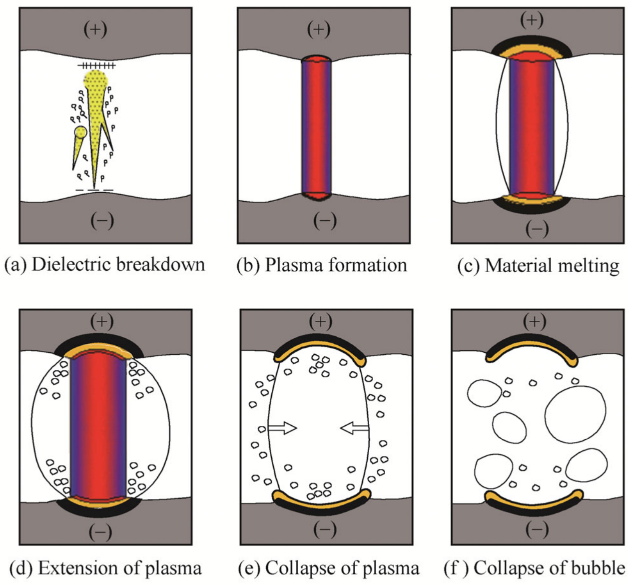

Fig. 1 Phases of electrical discharge

The unique material removal mechanism makes EDM insusceptible to the cutting forces caused by the contact between the workpiece and the tool electrode[3–4]. Therefore, it is suitable for machining on the micro-scale. Micro EDM

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is basically a scaled-down version of traditional macro EDM, which has a similar material removal mechanism as EDM. Micro EDM is suitable for machining micro holes, micro shafts and complex three-dimensional micro parts[5–9]. In fact, EDM can not only cut features on the micro- and submicro-scale, but also process features on the nano-scale[10–13]. As new products trend towards minimization, micro EDM has attracted a world-wide research attention, because of its potentially enormous economic benefits and research interest. It has been extensively researched for high-precision machining of a wide variety of conductive materials and even some ceramic materials with large design freedom at low set-up cost[14–18]. However, although the basic process mechanism of micro EDM is essentially analogous to traditional macro EDM, there are significant differences between the two machining methods in terms of tool fabrication, gap control, flushing of dielectric fluid, and machining technology[19–20]. The machining performances of micro EDM vary from those of traditional macro EDM, because of the micro-scaled tool electrodes and low electrical discharge energy.

Compared with macro EDM, the differences in the machining performances of micro EDM are derived from scale effects. Many influential factors that can be neglected in macro EDM must be closely considered when machining on the micro-scale[21]. Material microstructure, such as grain boundary and crystallographic orientation have a significant influence on the machining performances of micro EDM[22]. In addition, the material removal characteristics of micro EDM are extremely complex due to the very short pulse duration and very low discharge energy. As a result, the scale effects in micro EDM need to be researched in detail to effectively evaluate the influence of scale effects on micro EDM process.

In this paper, a new concept of "scale effects" in micro EDM was introduced and the abnormal machining performances of micro EDM were presented. Similarity theory was introduced to evaluate the scale effects in micro EDM. Single factor experiments were conducted and the similarity difference and similarity precision of the similarity system were analyzed and discussed.

2 Scale Effects in Micro EDM

2.1 Definition of scale effects in micro EDM

Micro EDM process is susceptible to many operating parameters, which are normally insignificant in macro EDM. Scale effects in micro EDM have not attracted enough research attention though they have been found by lots of researchers. Scale effects in micro EDM can be defined as the variation in the machining performances of micro EDM compared to conventional EDM, due to the change of operating parameters or the down-scaling of global or local geometric dimensions of the tool and workpiece electrodes.

2.2 Scale effects caused by material microstructure

A schematic diagram of micro and macro EDM of polycrystalline material is shown in Fig. 2. As can be seen from this diagram, when the electrode size adopted in micro EDM is sufficiently small, material removal occurs on the scale of a few grains or even within a single grain at a time. Thus, the material microstructure, including grain boundary, crystal defect and crystal orientation, must be considered when studying the micro EDM performances.

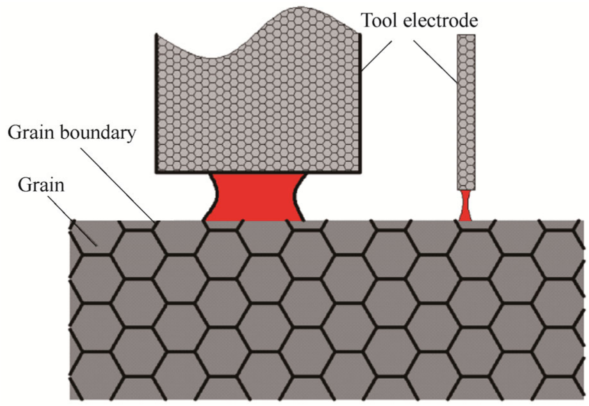

Fig. 2 Schematic diagram of micro and macro EDM of polycrystalline material

At the micro-scale, the workpiece metal can be considered to be a heterogeneous or multiphase material. For example, carbon steel microstructures are comprised of several phases such as ferrite, pearlite, and austenite, each of which has different physical characteristics[23]. Similarly, the crystalline grain and grain boundary can be regarded as a dispersed phase and continuous phases of a polycrystalline material. The stochastic distribution of grains results in the difference in grain boundary orientations between adjacent grains. Great lattice distortion and grain boundary segregation are produced at the grain boundary since the atoms are randomly arranged (Fig. 3). Therefore, the physical characteristics of the grain boundary differ from those of the grain, which produces differences in micro EDM performances.

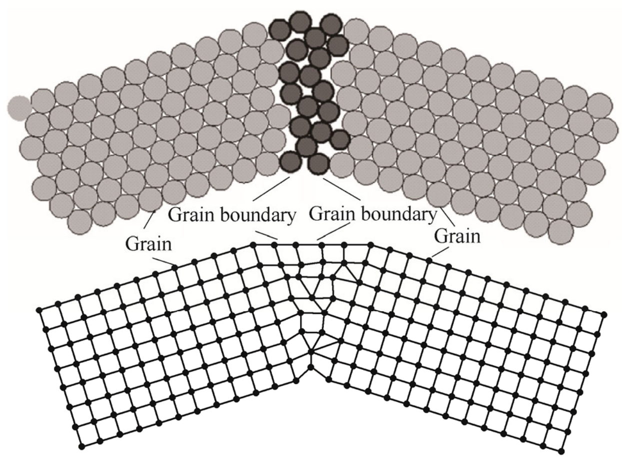

Fig. 3 Transitional structure model of grain boundary

LAUWERS, et al[24], found that the difference in thermal conductivity between the grain and grain boundary had influences on the material removal process of micro EDM. LI, et al[25], also found that the performances of micro EDM drilling of holes within a grain were different from those of drilling holes across grain boundary. Since crystalline lattices exhibit anisotropy, the machining performances of micro EDM vary with crystallographic orientation[26–27]. As a result, the EDM models based on the assumption that the workpiece material is homogeneous and isotropic may be inaccurate when applied to model micro EDM process.

2.3 Scale effects caused by processing parameters

The characteristics of material removal in micro EDM vary when scaling the processing parameters(pulse duration, electric current and open-circuit voltage, etc.) due to variations in the discharge conditions. Generally speaking, the variation in the material removal process in micro EDM is the key to the differences between the machining performances of micro and macro EDM.

KOJIMA, et al[28], indicated that in micro EDM there was insufficient time for heat conduction when the pulse duration is extremely short($<$5 μs); therefore, a large proportion of the discharge energy contributes to material removal. However, when longer pulse duration is adopted, the diameter of heat affected zone is much larger than that of molten zone, which indicates that a part of discharge energy is lost to the formation of the heat affected zone. Therefore, the pulse duration directly affects the machining performances of micro EDM.

When the discharge frequency is very high and the arc plasma doesn’t have sufficient time for complete expansion, the energy density and temperature are such high that a significant proportion of the material is removed by vaporization[29]. Since both the discharging gap and diameter of arc plasma of micro EDM are smaller than those of macro EDM, the power density of micro EDM can be approximately 30 times greater than that of macro EDM[30]. The energy efficiency of EDM with short pulse duration is much higher than that with long pulse duration due to higher power density[31]. The specific energy required to remove the workpiece material is greater at higher energy($>$50 μJ) compared to lower energy[32]. However, the material removal rate of micro EDM with short pulse duration is still low as a result of the lower discharge energy and that a significant portion of the produced heat is consumed as latent heat of vaporization.

Furthermore, the percentage of energy distributed into the workpiece and tool electrode during EDM vary with electrode materials, electrode shapes, dielectric types and electrical parameters[33–35]. As a result, since the material removal characteristics of micro EDM depend on the discharge energy, the predication of machining performances becomes difficult.

3 Similarity Evaluating Method

Similarity system theory can be used to quantitative analyze the scale effects, while the introduction of scale effects can only qualitative describe the differences between micro EDM and macro EDM. Using similarity theory, the functional relationships between the various physical quantities can be transformed into relationships between dimensionless groups. Similarity theory has been widely applied in experimental disciplines such as heat transfer theory, mass transfer theory and hydromechanics etc. However, until now, similarity theory has not been used to analyze the variation in EDM performances. Since micro EDM process is governed by many parameters, expensive experiments and difficult mathematical calculations are needed to analyze their influences. The adoption of similarity theory can facilitate the establishment of an empirical process model even without an exact mathematical description[36].

3.1 Similarity difference and similarity precision

The objective of the study of scale effects in micro EDM is not only to describe the differences in machining performances between micro EDM and macro EDM, but also to quantify these differences when down-scaling the EDM system. It can be assumed that one system is similar to another when there are some similar elements between the two systems and then the two systems are called similarity systems[37]. Similarity system theory is an effective method for investigating similarity and the origin of similarity[38–39]. Therefore, the concepts of similarity system, similarity difference and similarity precision are introduced to evaluate scale effects in micro EDM. The quantification of similarity can be obtained by the number of elements and the value of the similarity unit of the two similarity systems.

Assume that there are two sets, M and N in a conventional micro EDM system which contains m geometric elements and n non-geometric elements, respectively. The expressions can be written as

$$M=\{S_1,S_2,\cdots,S_m\}, \tag{1}$$

$$N=\{T_1,T_2,\cdots,T_n\}. \tag{2}$$

Where the geometric elements contain the geometric conditions of the electrodes and various processing parameters, while the non-geometric elements involve the evaluation index of EDM performances. Correspondingly, there are m geometric elements and n non-geometric elements in the sets of $\bar{M}$ and $\bar{N}$ in the other micro EDM system. The expressions for these can be given as

$$\bar{M}=\{\bar{S}_1,\bar{S}_2,\cdots,\bar{S}_m\}, \tag{3}$$

$$\bar{N} = \{\bar{T}_1, \bar{T}_2, \cdots, \bar{T}_n\}. \tag{4}$$

If the geometric similarity degree r_L is kept constant, there is

$$\frac{\bar{S}_1}{S_1} = \frac{\bar{S}_2}{S_2} = \cdots = \frac{\bar{S}_m}{S_m} = r_L. \tag{5}$$

Then, the non-geometric similarity degree r_{T_i} can be expressed as

$$\frac{\bar{T}_{\bar{i}}}{T_i} = r_{T_i}. \tag{6}$$

The similarity difference and similarity precision can be given as follows[40–41]:

$$\varphi_i = r_{T_i} - r_L^K, \tag{7}$$

$$\Phi_i = \frac{r_{T_i} - r_L^K}{r_L^K}, \tag{8}$$

where φ_i is the similarity difference, Φ_i is the similarity precision and K is the power degree of the geometric similarity degree r_L.

The value of Φ_i denotes the degree of the deviation between non-geometric similarity elements and geometric similarity degree. Hence, it can be observed that:

(1) If $\Phi_i = 0$, then non-geometric similarity degree is equal to geometric similarity degree, elements are precisely similar.

(2) If $\Phi_i < 0$, non-geometric similarity degree is less than geometric similarity degree, it can be called negative scale effect.

(3) If $\Phi_i > 0$, non-geometric similarity degree is more than geometric similarity degree, it can be called positive scale effect.

It can be concluded that the index of similarity precision can not only represent the deviation degree between non-geometric similarity degree and geometric similarity degree, but can also indicate the direction of deviation. The larger the absolute values of similarity difference and similarity precision, the greater the deviation.

The similarity precision and similarity difference are dimensionless values, which denote the degree of the deviation between geometric elements and non-geometric elements. In this study, capacitance and open-circuit voltage were considered to be geometric elements while the machining time was considered to be non-geometric elements. Thus, all the capacitances or open-circuit voltages and their corresponding machining times can be regarded as a micro EDM system while the maximum capacitances or open-circuit voltage and its corresponding machining time compose the other micro EDM system. It is then concluded that the micro EDM system with higher values of similarity precision and similarity difference is more susceptible to scale effects.

3.2 Similarity evaluation of scale effects in micro EDM

Single factor experiments were conducted to verify the feasibility of using the similarity theory to evaluate the scale effects in micro EDM. These experiments were performed on a micro EDM machine where a resistor-capacitor(RC) circuit was used to supply power for the spark discharge. A simple cylindrical tungsten rod with diameter of 200 μm was used as the tool electrode. The workpiece was austenitic stainless steel with thickness of 300 μm which was maintained at positive polarity in the experiments. The rotation speed of the tool electrode was 2000 rpm and the feed depth was 200 μm. Mineral oil was used as the dielectric medium. The machining parameters of micro EDM are listed in Table 1.

Table 1. Machining parameters for the single factor experiments

Experiment No.	Capacitance C/pF	Open-circuit voltage U/V
1	1000	70, 80, 90, 100, 110
2	220, 470, 1000, 2200, 4700	80

3.2.1 Similarity evaluation of scale effects resulting from capacitance

The similarity degree, similarity difference and similarity precision of the machining time depending on the scale of capacitance is shown in Table 2. These parameters were calculated using Eqs. (5)–(8). The discharge energy can be given as

$$W = \frac{1}{2} C U^2, \tag{9}$$

where W is discharge energy of a single discharge spark, C is the capacitance and U is the open-circuit voltage. Since machining time is determined by the discharge energy, it is assigned that K=1, because the power degree of capacitance is 1.

Table 2. Appraisal table of similarity of machining time depending on capacitance

Capacitance C/pF	4700	2200	1000	470	220
Machining time t/s	240	323	446	833	1294
Geometry ratio r_L	1	0.47	0.21	0.1	0.05
Similarity degree r_{T_i}	1	1.35	1.85	3.47	5.38
Similarity difference φ_i	0	0.88	1.64	3.37	5.34
Similarity precision Φ_i	0	1.87	7.72	33.67	114.03

The similarity difference and similarity precision of machining time based on the capacitance are shown in Fig. 4. As can be seen, the scale effect caused by capacitance is positive scale effect. As the data shown, the lower the scale of capacitance, the higher the deviation of similarity difference and similarity precision, which means the micro scale effects become more intense with the decreasing scale of capacitance. Moreover, the evolution of similarity precision is more significant than the similarity difference when the capacitance is scaled down. The largest similarity difference is 5.34 while the largest similarity precision can be as high as 114.03. Therefore, it can be concluded that the similarity precision can more effective reflect the scale effects and their fluctuation than the similarity difference.

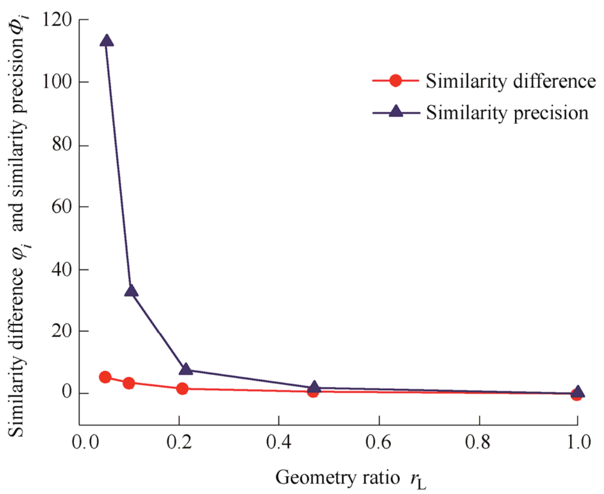

Fig. 4. Relationships among similarity difference, similarity precision of the machining time and the scale of capacitance

3.2.2 *Similarity evaluation of scale effects resulting from open-circuit voltage*

The similarity degree, similarity difference and similarity precision of the machining time depending on the scale of open-circuit voltage were calculated using Eqs. (5)–(8). The results are shown in Table 3, where specify 2 for the *K* because the power degree of open-circuit voltage *U* is 2.

Table 3. Appraisal table of similarity of machining time depending on open-circuit voltage

Open-circuit voltage U/V	110	100	90	80	70
Machining time t/s	385	397	491	547	1122
Geometry ratio r_L	1	0.91	0.82	0.73	0.64
Similarity degree r_{T_i}	1	1.03	1.28	1.42	2.91
Similarity difference φ_i	0	0.20	0.61	0.89	2.51
Similarity precision Φ_i	0	0.23	0.74	1.23	3.94

The similarity difference and similarity precision of machining time depending on the scale of open-circuit voltage are shown in Fig. 5. It shows that the influence of machining time is positive scale effect, the similarity difference and similarity precision increase with the decrease of the scale of open-circuit voltage. When the geometry scale is greater than 0.7, the similarity difference and similarity precision experience a slight change. But, when the geometry scale is less than 0.7, the scale effects become more intense with the decrease in open-circuit voltage. As a result, the similarity difference and the similarity precision can be used to quantitative evaluate the scale effects in micro EDM. The similarity theory is appropriate for application in the evaluation of the scale effects in micro EDM.

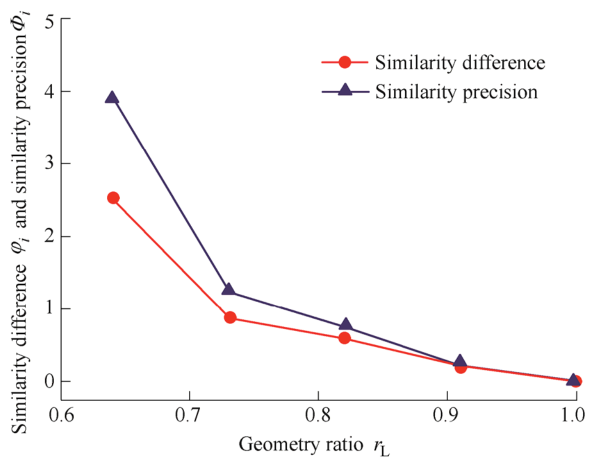

Fig. 5. Relationships among similarity difference, similarity precision of the machining time and the scale of open-circuit voltage

4 Conclusions

(1) Scale effects in micro EDM is a new concept similarity theory is introduced to evaluate the scale effects in micro EDM..

(2) Low discharge energy, short pulse duration, small tool size and small discharge crater size are responsible for the occurrence of scale effects in micro EDM.

(3) The lower the capacitance or open-circuit voltage employed in micro EDM, the higher the change in similarity precision, which means the scale effects increase with the decrease of discharge parameters.

(4) When scaling-down the capacitance or open-circuit voltage, the evolution of similarity difference is mild, while similarity precision increases significantly. Similarity precision can more effectively reflect the scale effects and their fluctuation than the similarity difference.

(5) Similarity theory is suitable for evaluating the scale effects in micro EDM and the study of scale effects is helpful in predicting and optimizing the machining performances of micro EDM.

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