Estimation of Material Removal Volume of a Micro-EDM Drilled Hole Using Discharge Pulse Monitoring

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KEYWORDS : Micromachining, Electrical discharge machining, Manufacturing process, Tool monitoring

When drilling using electrical-discharge machining (EDM), severe electrode wear makes in-process measurements of the depth of the drilled hole and the volume of material removed impossible. To estimate the volume of material removed a reliable real-time discharge pulse counting method is proposed by assuming that the volume removed in EDM is proportional to the number of discharge pulses from an iso-energy pulse generator. The geometry of machined holes, including depths and cross-sectional profiles, is estimated using geometric analysis. A proportional relationship between the volume of material removed and the number of discharge pulses was developed and verified by experiments.

Manuscript received: 18 May, 2007 / Accepted: 1 August, 2007

1. Introduction

Recently many electrical machining methods have been investigated for 3-D micromachining.[1-5] Especially, electrical discharge machining (EDM) is one of the most frequently used non-conventional industrial machining methods. EDM can be applied to most conductive materials regardless of their hardness because it uses the thermal energy generated by electrical discharge plasma to remove material. Microholes fabricated by drilling using EDM have been applied to many industrial fields in recent years.[1-4]

In conventional mechanical drilling, the material removal rate (MRR), which is the volume removed from the workpiece per unit time, is determined from the feed rate of the drilling tool. However, in the EDM process, the electrode and the workpiece erode at a prescribed tool wear ratio (TWR), which is defined as the ratio of material removed from the electrode to that removed from the workpiece. Therefore, to precisely estimate the machined depth when drilling using EDM, the vertical position of the tip of the tool electrode is measured by frequently contacting the tool tip with a reference block.[6]

To prevent frequent interruption of machining to measure the tool tip position, we propose a method based on counting the discharge pulses to estimate the volume of material removed. The approach assumes that the volume removed per discharge pulse is consistent if the discharge energy per pulse remains the same. Previously reported research supports the assumption that the amount of material removed is closely related to the energy discharged. Wykes *et al.*[7] demonstrated that the MRR, TWR, and surface roughness of EDM processes are significantly affected by the current intensity and the pulse duration, which determine the discharge energy. Weck *et al.*[8] obtained a proportional relationship between the workpiece weight and mean discharge time in a transistor EDM sinking machine.

Chang[9] used a gap control on a die-sinking EDM to generate iso-pulses with the same ignition delay time. The method generated the same discharge energy in a transistor discharge circuit and resulted in an eroded depth proportional to the machining time. Therefore, they resolved the electrode wear problem by obtaining a constant MRR in the workpiece. Bleys *et al.*[10,11] developed simplified tool-wear sensing based on an efficiency factor[12] for real-time wear compensation in milli-sized milling using EDM with a transistor iso-energy pulse generator. However, further development of micro-EDM is required because of accuracy problems.[6] Han *et al.*[13] integrated a transistor iso-pulse generator capable of generating small iso-duration discharge current pulses appropriate for micro-EDM. However, on-line measurement of the ignition delay and the discharge time of a transistor EDM process is not easy to implement. Experimental results by Wong *et al.*[14] show that the volume of the micro-crater created by a single discharge varies with the discharge energy when a resistor-capacitor (RC) EDM pulse circuit is used.

We also used an RC pulse circuit for our research instead of a transistor circuit. An RC circuit can generate finer pulses by adjusting the resistance and capacitance values, while the energy of the pulses can be controlled by the capacitance alone. We focused on verifying the relationship between the volume of material removed from the workpiece and the number of discharge pulses used for drilling with micro-EDM. Based on this research, we propose a new method of estimating the amount of material machined. The number of discharge pulses is measured by real-time monitoring of the gap voltage between the electrode and workpiece in an RC discharge circuit, as described in Section 2. In Section 3, the volume and depth of material removed from the workpiece are estimated. The method was verified experimentally by fabricating holes with a variety of drilling depths.

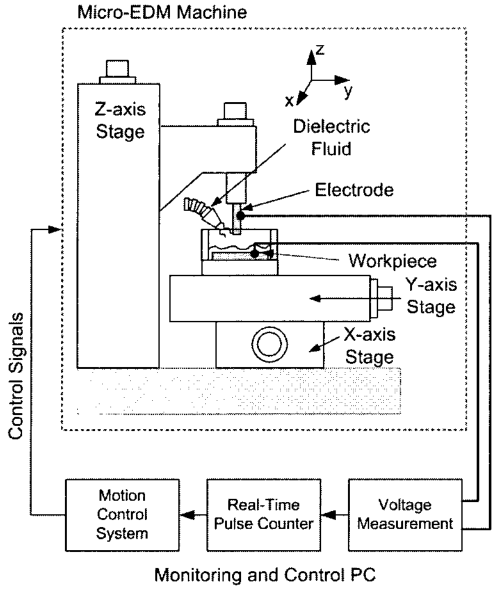


Fig. 1 Schematic diagram of the experimental setup

2. Discharge pulse counting to measure the amount of material removed

2.1 EDM machine tool setup

Figure 1 shows a schematic diagram of the experimental setup. The motion system of the EDM machine consisted of a three-axis linear stage and a spindle. The gap voltage between the electrode and the workpiece was measured using a real-time data acquisition board (PXI-5112, National Instruments) in a PC (PXI-1042Q, National Instruments) to monitor and control the micro-EDM machine. Fast and reliable process control was achieved by integrating the control and monitoring boards in one PC. The measured voltage signal was used to count the discharge pulses in real time by designing a simple algorithm. The number of discharge pulses was transferred to the motion control module. The electrical power supply system for the EDM was interfaced with a general-purpose interface bus to the control PC. Therefore, the applied gap voltage could be adjusted synchronously as programmed in the machine control unit. During the EDM process, kerosene was continuously circulated as a dielectric insulating layer.

2.2 RC discharge pulse generator

In general, a transistor pulse generator provides a higher MRR since it gives a high discharge frequency because there is no capacitor charging time. However, the discharge duration varies with the discharge delay time, depending on the gap condition, and a discharge cannot be generated if the delay time is longer than the time that the pulse is turned on. Therefore, it is difficult to generate iso-duration pulses that are sufficiently short for micro-EDM.[13]

An RC discharge pulse generator can be used to generate short iso-duration pulses by adjusting the capacitance value, because the extremely small resistance of the plasma channel induced by the discharge spark can be ignored. A schematic drawing of an RC discharge pulse generating circuit is shown in Fig. 2. The electrical energy generated by a single discharge (E_S) can be expressed as

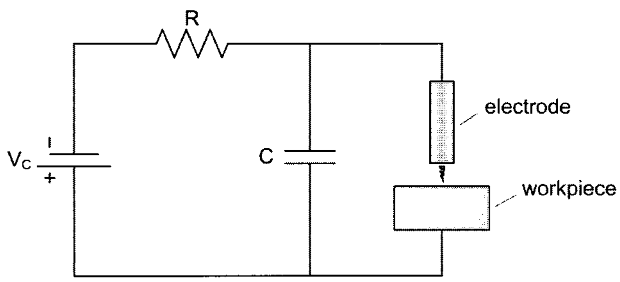


Fig. 2 RC discharge pulse generation circuit

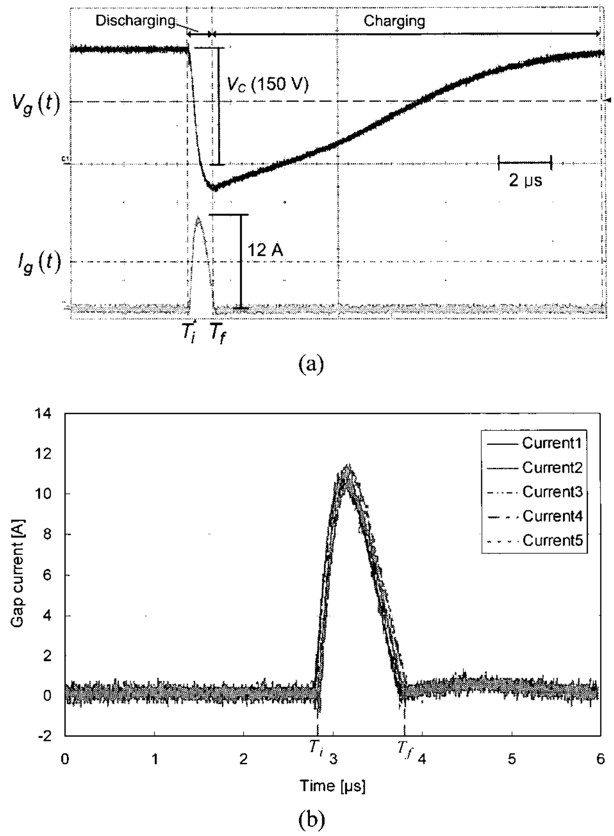


Fig. 3 Monitoring the gap voltage and current when a discharge occurs: (a) captured waveform; (b) comparison of five gap current waveforms

$$E_S = \int_{T_i}^{T_f} V_g(t) I_g(t) dt \tag{1}$$

where T_i and T_f are the start and finish times of the discharge current. Figure 3(a) depicts the measured gap voltage (V_g) and current (I_g) waveforms when an electric discharge occurs with a supplied voltage of 150 V. The measured gap currents overlapped well and had a uniform shape, as shown in Fig. 3(b), proving that pulses with the same energy can be generated by using an RC pulse generator.

2.3 Counting discharge pulses

The monitored gap voltage between the electrode and workpiece was used to count the number of discharge pulses. A simple digital logic algorithm was developed based on the fact that the voltage drop and restoration occur successively for each discharge pulse in the RC discharge pulse generation circuit. The counting procedure is shown schematically in Figure 4. When the measured gap voltage is below the reference voltage (V_{ref}) at the sampling time, the discharge flag obtains a value of 1 (TRUE); otherwise, it has a value of 0 (FALSE). The number of discharge pulses is increased by 1 only when the value of the discharge flag changes from 0 to 1. This gives the total number of discharge pulses in real time. These logical operations proceed in the same PC that controls the motion system, so any time delay at the interface between the instruments is almost negligible.

2.4 Relationship between the pulse count and volume of material removed

We investigated the proportional relationship between the volume of material removed from the workpiece and the number of discharge pulses using the following two assumptions.

1) An RC discharge circuit generates a succession of discharges

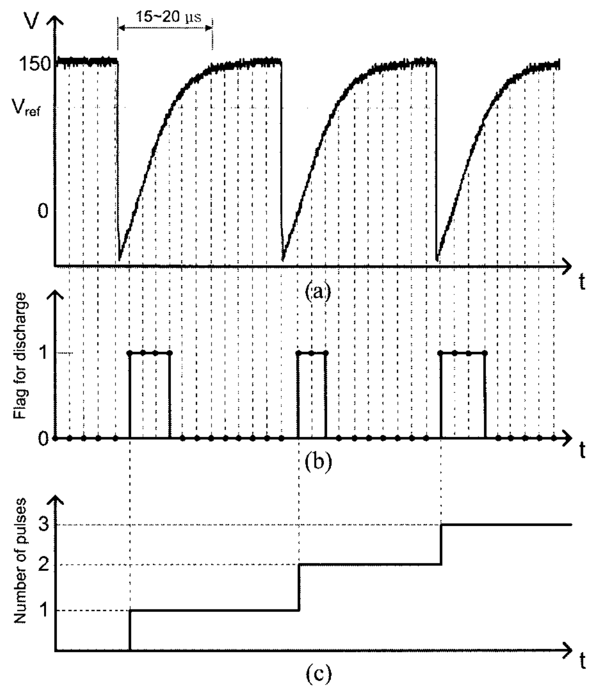


Fig. 4 Schematic diagram of the method used to count discharge pulses: (a) gap voltage; (b) discharge state signal (discharge flag); (c) number of discharge pulses (N_P)

with the same energy. Microscopic analysis of individual spark profiles[15] has shown that the energy of the discharge plasma channel differs with the shape and size of the spark due to various hard-to-measure parameters such as the gap distance, electric field between the gap, and dielectric fluid conditions. However, minute energy differences in hundreds of thousands to millions of discharges can be ignored as random errors of a stochastically normalized mean.

2) The volume of material removed from a workpiece by a given amount of energy discharge remains constant. Thus, factors such as the increase in the micro-hardness of the white layer that is generated by the electrical-discharge-machined surface[16] or the generation of ineffective sparks from contaminated gaps due to debris are neglected for the same reason given in 1).

Therefore, the total volume removed from a workpiece by EDM has the following relationship:

$$Vol_{Total} = Vol_S \cdot N_P \tag{2}$$

where Vol_{Total}, Vol_S, and N_P are the total volume of material removed from the workpiece, the volume of material removed from the workpiece per discharge pulse, and the number of discharge pulses, respectively. The relationship shown in Equation (2) is experimentally verified in Section 3.2.

Table 1 EDM conditions for drilling

Experiment conditions	Value
Open circuit voltage (V)	150
Circuit capacitance (μF)	0.2
Circuit resistance (Ω)	200
Rotational speed of spindle (rpm)	200
Electrode diameter (μm) / material	300 / tungsten carbide
Workpiece material	SKD11
Dielectric fluid	Kerosene

3. Experimental results

3.1 Experimental conditions

To identify the relationship between the volume of material removed from the workpiece and the number of discharge pulses, holes were drilled by EDM using different numbers of discharge pulses. The machining conditions are listed in Table 1.

The method typically used to find the volume of material removed is to measure its weight. However, this method is difficult to implement for micro-EDM because the difference in weight before and after machining is small. Therefore, we obtained the volume of material removed by geometric analysis of the cross-section of the machined hole.

3.2 Calculation of the volume of material removed

Holes were drilled using four different numbers of discharge pulses. Each hole was drilled three times to improve the reliability of the measurements. After drilling the holes around the edges of the workpiece, the half of the hole closer to the edge of the workpiece was removed using additional EDM processes. The position of the electrode was carefully adjusted to cut through the center of the hole while considering static factors such as the electrode diameter and side-sparking distance, as well as erratic runout from electrode replacement. Cross-sectional images of the drilled holes were captured by a CCD camera attached to a microscope. Points on the edges of the cross-sectional image were extracted using image processing. The images on the left of Figure 5 show the machined holes, while those on the right show the cross-sectional profiles obtained by image processing.

Integrals of functions fitted to the hole shape were used to simplify the calculations of the volume of material removed. The cross-sectional profiles of the machined holes shown in Fig. 5 fit the following hyperbolic curve equation well:

$$z = \frac{-a}{x-b} - \frac{a}{b} \tag{3}$$

where x and z are the axis variables of the coordinate system used in Fig. 5, and a and b are the curve-fitting parameters. Examples of the curve-fit results are shown in Fig. 6.

The directional flow of the dielectric fluid in the hole during machining can result in an asymmetric cross-sectional geometry.[17] This asymmetry can be calculated from:

$$d_{Asymmetry} = \frac{A_{Right} - A_{Left}}{A_{Right}} \tag{4}$$

where $d_{Assymetry}$ is the degree of asymmetry, and A_{Left} and A_{Right} are the left- and right-side areas of the hole, respectively. The degree of asymmetry of all the machined holes was under ± 4%. Therefore it is reasonable to assume for simplicity that the cross-sections of the machined holes were symmetric.

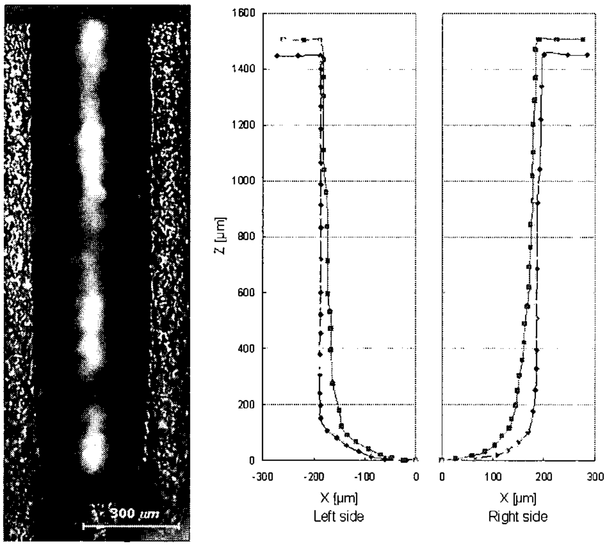
If the cross-section of a hole is assumed to be symmetric, its volume can be calculated using a simple volumetric integral of Equation (3):

$$\begin{aligned} Vol &= \int_0^{z_d} \pi \left(\frac{b^2 z}{bz+a} \right)^2 dz \\ &= \pi \left[b^2 z_d - 2ab\{\ln(bz_d + a) - \ln a\} + \frac{bz_d}{a(bz_d + a)} \right] \end{aligned} \tag{5}$$

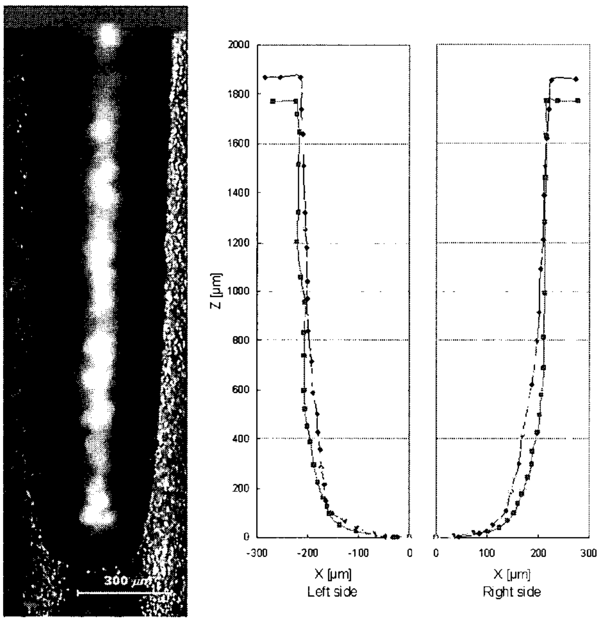
where Vol and z_d are the volume and the depth of the machined hole, respectively. The removed volume Vol estimated from Equation (5) using the measured depth z_d and the curve-fitting parameters a and b is also shown in Table 2.

Table 2 Curve fitting results and the machined amounts of holes

Desired N_P ($\times 10^3$)	Measured N_P	Curve fitting parameters		Depth of hole		Volume of hole	
		a	b	z_d (μm)	Average (μm)	Vol ($\times 10^6 \mu m^3$)	Average ($\times 10^6 \mu m^3$)
500	500090	2900	192	575.24	577.21 ± 7.10	5.38E+07	52.4 ± 4
	500093	5000	206	571.3		5.55E+07	
	500062	4900	190	585.09		4.78E+07	
1000	1000140	8500	204	1036.2	1046.73 ± 14.9	1.00E+08	98.7 ± 1.34
	1000270	7500	196	1063.8		9.74E+07	
	1000140	8000	201	1040.2		9.87E+07	
1500	1500020	2500	194	1449.9	1482.1 ± 29.27	1.57E+08	144 ± 16.66
	1500070	3500	190	1489.3		1.51E+08	
	1500180	10700	188	1507.1		1.25E+08	
2000	2000250	11000	223	1773	1817 ± 43.36	2.21E+08	201 ± 18.01
	2000260	17000	213	1818.3		1.87E+08	
	2000230	15000	211	1859.7		1.94E+08	

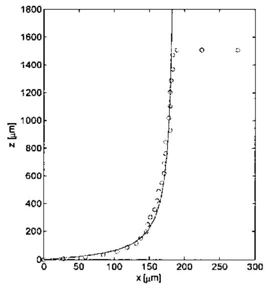


(a)

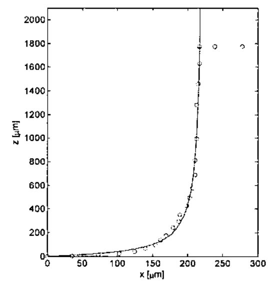


(b)

Fig. 5 Cross-sections of the machined holes (left) and their profiles obtained using image processing (right): (a) $N_P = 1.5 \times 10^6$; (b) $N_P = 2 \times 10^6$



(a)



(b)

Fig. 6 Examples of curve-fit results: (a) $N_P = 1.5 \times 10^6$; (b) $N_P = 2 \times 10^6$

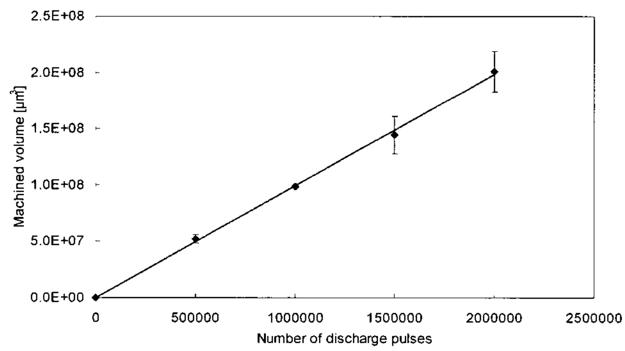


Fig. 7 Relationship between machined volume and number of discharge pulses

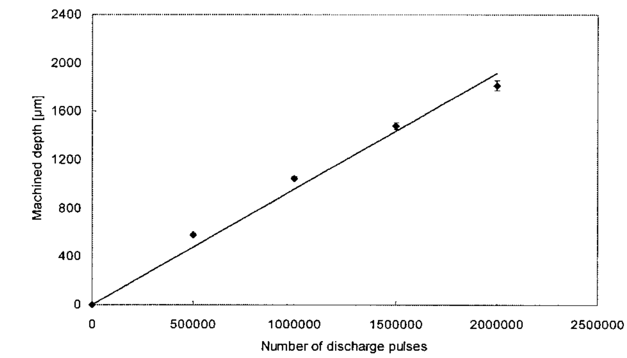


Fig. 8 Relationship between machined depth and number of discharge pulses

Experimental verification of the proportional relationship between the machined volume and the number of discharge pulses is shown in Fig. 7. The experimental results up to 1,000,000 discharge pulses (aspect ratio of 3) follow a linear relationship well. However, for deep holes (over 1,500,000 pulses), the results have higher standard deviations, and the error is 11.1 %. The sources of the error were as follows.

1) Only one side of the cross-sectional profile was used based on the assumption of symmetric hole geometry; asymmetric holes introduced errors in the estimations.
2) The effects of debris, such as abnormal discharges, became significant as the depth of hole increased since flushing is ineffective in a deep hole.

The relationship between the machined depth and the number of discharge pulses is useful to estimate the in-process material removal when drilling using EDM. However, the machined depth is not perfectly proportional to the pulse number because of runout, debris effects in deep holes, and variations in the hole diameter with respect to the hole depth due to side wear. Nevertheless, the relationship between the machined depth of the hole and the number of discharge pulses is described well by the straight line shown in Fig. 8. This result was obtained by examining aspect ratios up to 5.

4. Conclusions

A new method was proposed to estimate the amount of material removed and determine the machined volume and depth of a micro-hole when drilling using EDM. We used on-line monitoring of the number of discharge pulses to provide in-process estimation. A simple and fast pulse-counting algorithm was designed and implemented using a high-speed data acquisition board for real-time applications. The experimental results obtained from analyzing the cross-sections of machined holes show that the machined volumes of the drilled holes were proportional to the number of discharge pulses.

If the proposed method is applied to accurate depth control of micro blind-hole machining it can reduce the machining time significantly by eliminating the current time-consuming procedures for machining depth measurements, which require frequent resetting of the electrode tip position. The proposed method can also be applied to milling using EDM as a tool wear compensation scheme.

ACKNOWLEDGEMENT

This work was supported by the Industrial Technology Development Program of the Ministry of Commerce, Industry and Energy, Republic of Korea.

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