International Journal of Engineering Materials and Manufacture (2022) 7(2) 54-60
https://doi.org/10.26776/ijemm.07.02.2022.02

Comparative Study of Material Removal Rate of Single-Spark and Multi-Spark Micro-EDM of Copper

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Received: 03 April 2022
Accepted: 13 April 2022
Published: 16 April 2022
Publisher: Deer Hill Publications

ABSTRACT
Micro-electro discharge machining (micro-EDM), a noncontact material removal process, is a well-established technique for making mold cavity on any workpiece materials having a minimal electrical conductivity of 0.1 Scm^{-1}. The spark between tool electrode (-ve) and workpiece electrode (+ve) removes materials mostly from workpiece. Knowing the time and amount of material removed in a single spark, MRR can be estimated. A number of analytical study have been reported for the estimation of MRR based on the ideal situation single-spark erosion. In case of multi-spark micro-EDM, charging and discharging do not always follow the ideal conditions of the circuit and a lot of unwanted pulses such as arching and short circuit are produced which in turn reduce the effective number of pulses per second. Moreover, in RC pulse micro-EDM, the discharges are not uniform and the current and voltage are not constant with time. As a consequence, the performances estimated based on single-spark erosion formula could be misleading in multi-spark cases. This paper presents an analytical estimation of MRR as a function of machining parameters capacitance and voltage for single spark which is then compared with the multi-spark erosion of RC pulse micro-EDM. The single spark erosion rate is estimated using the electro-thermal theories in which charging and discharging duration are derived from the RC pulse time constant and the number of sparks per unit time is counted from the single spark duration. The expression of single spark erosion volume is estimated using heat transfer equations. It is also difficult to conduct single-spark EDM experiment and it has very little practical implications. Experiments are conducted to investigate the multi-spark erosion rate. It is shown that, theoretically, the number of sparks depends on the capacitance and resistance of the circuit. However, in multi-spark erosion, it is found that the number of effective sparks depend not only the capacitance and voltages but also the conditions of micro-EDM such as the workpiece and tool materials, flushing conditions, depth of cut. It is shown that the multi-spark MRR is almost half of the calculated value which is found using the equation of single spark MRR in micro-EDM of copper. Therefore, the single spark erosion formula needs to be adjusted for each of the workpiece to incorporate with the multi-spark erosion in real conditions.
Keywords: Micro-electro discharge machining, material removal rate, time constant, multi-spark, nonconductive ceramic

Nomenclature
C = Capacitance (F)
c_p = Specific heat at constant pressure (J/KgK)
E = Total circuit energy per spark (J)
E_w = Energy absorbed by workpiece (J)
H_m = Heat of melting (J/Kg)
H_v = Heat of vaporization (J/Kg)
k = Fraction of total energy consumed for material removal
k_1 = Fraction of E_w used for material removal by melting
k_2 = Fraction of E_w used for material removal by vaporization

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Reference: Ali et al. (2022). Comparative Study of Material Removal Rate of Single-Spark and Multi-Spark Micro-EDM of Copper. *International Journal of Engineering Materials and Manufacture*, 7(2), 54-60.

L_m = Latent heat of melting (J/Kg)
L_v = Latent heat of vaporization (J/Kg)
N_s = No of sparks per second
R = Resistance (Ω)
T = Temperature (K)
T_b = Boiling temperature (K)
t_c = Capacitance charging time (s)
t_{dc} = Capacitance discharging time (s)
T_i = Initial temperature (K)
T_m = Melting temperature (K)
V = Voltage (V)
V_C = Voltage between capacitance terminals (V)
V_r = Material removed by vaporization and melting (mm^3)
V_R = Voltage drop over the resistance (V)
ρ = Density of the workpiece material (Kg/mm^3)
τ = Time constant circuit (s)

1 Introduction

Micro-electro discharge machining (micro-EDM), a noncontact material removal process, is a suitable technique for microstructuring of any material having a minimal electrical conductivity of 0.1 Scm^{-1}. A series of electrical sparks or discharges occur rapidly in a short span of time between tool electrode and workpiece during micro-EDM [1, 2]. The electrical energy is converted into thermal energy instantaneously in micro-EDM and spark energy results in melting and vaporization of both the workpiece and tool materials [3-6]. About 90% of the molten material is removed by vaporization and the material beneath the surface gets less energy which is removed by melting [6]. In micro-EDM, the material is removed precisely by low level of input energy [7]. Therefore, an RC circuit is used in micro-EDM for pulse creation due to its capability of producing very small energy with a significantly short pulse in nanosecond duration [7].

The main process characteristics of micro-EDM are material removal rate (*MRR*), average surface roughness and tool wear ratio. During micro-EDM, workpiece material is removed by thermal energy created due to the impingement of ion or electrons. Thus, every spark removes specific amount of material. Knowing the time and amount of material removed in a single spark, *MRR* is estimated as micro-EDM process characteristics. However, *MRR* is greatly influenced by the discharge duration and peak current even the same materials of both the electrode and workpiece. Longer discharge duration and a higher peak current result in a higher *MRR* and *TWR* with poor surface finish. On the contrary, a longer discharge duration and lower peak current reduce *MRR* with better surface roughness and a lower *TWR* [8, 9]. The *MRR* also depends upon the properties of the workpiece material, the tool material and dielectric fluid. The lower breakdown voltage causes an earlier occurrence of spark, which increases the *MRR*. Since Cu has a lower breakdown voltage than CuW, a higher *MRR* is obtained in micro-EDM of Al_2O_3 with a Cu electrode [10].

A number of analytical study have been reported for the estimation of micro-EDM characteristics [11] which are developed based on amount of material removed in a single spark considering the ideal situations. These models could not include some of the effects that play a vital role in real micro-EDM process and it is recommended to consider the effect of multi-spark machining [12, 13]. In multi-spark micro-EDM, charging and discharging do not always follow the ideal conditions of the circuit [14], and a lot of unwanted pulses such as arching and short circuit are produced [15] which in turn reduce the effective number of pulses per second. Moreover, in RC pulse micro-EDM, the discharges are not uniform and the current and voltage are not constant with time [11]. As a consequence, the performances would not be same as estimated by single spark erosion and should be modified for multi-spark machining conditions. This paper presents a simple analytical estimation of *MRR* as a function of machining parameters capacitance and voltage for single spark which is then compared with the multi-spark erosion of RC pulse micro-EDM.

2 Single Spark Micro-EDM

To make a comparison between single spark and multi-spark erosion rate, an equation of *MRR* hence developed considering the ideal conditions in RC pulse micro-EDM. For single spark analysis the following assumptions are considered.

1. The workpiece and tool materials are homogeneous in nature.
2. The thermo-physical properties of the workpiece material remain constant during the machining process [3].
3. A fraction of the total spark energy is absorbed into the workpiece by conduction and rest of the energy is dissipated to the surroundings by convection and radiation [6].
4. The entire material is removed from the cavity after each discharge [16] and debris is not resolidified inside or around the cavity.
5. The capacitor has no initial voltage and it is charged from a constant voltage source.
6. Ignition delay time is negligible compared to total charging and discharging time.

A diagram of a RC pulse micro-EDM circuit with the voltages at different parts is shown in Fig. 1. It has mainly two parts; the charging part is connected to a high resistor in series and the discharging part has no resistor or is connected to a very low resistor. The energy stored in the capacitor during the charging period is completely released through the gap. The energy discharged (E) in a single spark micro-EDM is given by Eqn. (1) where C is the capacitance and V is the voltage gap.

$$E = \frac{1}{2}CV^2 \quad (1)$$

Thus, charging and discharging time depends on the amount of capacitance and resistances connected to the circuit. To make a very quick discharge, generally the discharge circuit is kept resistance-free in the ideal condition. However, the discharging circuit exerts small resistance from dielectric fluid and the machine system. It is obvious that the smaller the time constant, the more rapidly the voltage gain or decrease that is, the faster the response and the quicker the dissipation of circuit energy [17].

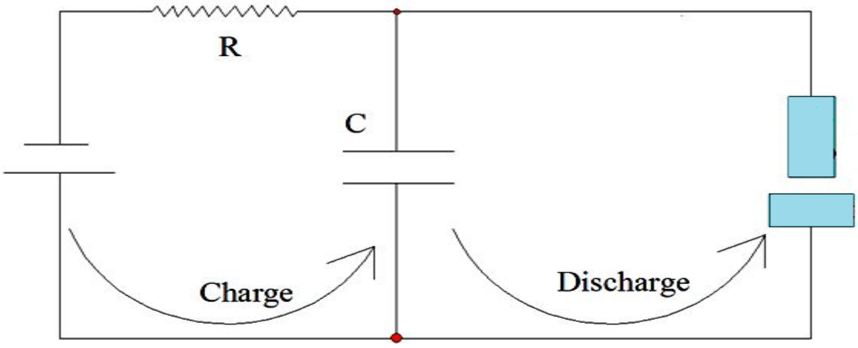

Figure 1. Schematic diagram of a RC pulse micro-EDM circuit showing the voltages in different parts of charging side

2.1 Estimation of Material Removal per Spark

The single spark energy of a RC micro-EDM circuit as expressed by Eqn. (1) is not utilized completely for material removal of the workpiece. Only a fraction of the spark energy causes melting and vaporization of the material and creates a micro-crater. The remaining energy supplied into the gap is lost to the surroundings. Assuming k fraction of E is utilized to remove material by melting and vaporization, thus, the discharged energy used for material removal per spark, E_w is given by:

$$E_w = \frac{1}{2}kCV^2 \quad (2)$$

The value of k depends upon the thermal properties of the workpiece material. It is observed that the material is removed by vaporization (during the discharge) and melting (during the charging) [6]. Assuming, k_1 fraction of E_w is used to vaporize the material and k_2 fraction of E_w is used to melt the material only. Thus, the volume of material removed per spark can be found using Eqn. (3).

$$V_r = \frac{kCV^2}{2}\left[\frac{k_1}{\rho H_v} + \frac{k_2}{\rho H_m}\right] \quad (3)$$

According to Equation (3), the crater volume is the function of capacitance, voltage and volumetric heat of vaporization and melting. Thus, material removal is controlled by both the electrical parameters and thermal properties of the work material in RC pulse micro-EDM.

The number of sparks can be found from the RC circuit charging and discharging period estimation. It is observed that each spark has three stages. In the first stage, the discharge circuit is kept off, the charges are stored in the capacitor from the electric source and the capacitor voltage rises to its full capacity from zero while its current decreases to zero. The first stage is called charging or pulse-off time. In the second stage, dielectric breakdown occurs under the electromagnetic field, the resistance between the tool electrode and the workpiece decreases to zero. The second stage is referred to as ignition delay time. In the third stage, when there is virtually no resistance between the tool electrode and the workpiece, spark occurs with high current. The capacitance voltage decreases to zero. This stage is called discharging or pulse-on time. In this study, ignition delay time is assumed negligible compared to the total charging and discharging time. Therefore, the total time required for single spark in a RC pulse circuit is the summation of charging and discharging time of capacitor. Total number of sparks per second (N_s), is the reciprocal of total time required for single spark and it can be expressed by Equation (4).

$$N_s = \frac{1}{t_c + t_{dc}} = \frac{1}{5R_1C + 5R_2C} = \frac{1}{5C(R_1 + R_2)} \quad (4))$$

The total number of sparks in unit time is the function of capacitance and resistances. Therefore, N_s can be increased or decreased by changing either the capacitance or resistances or both in a RC pulse micro-EDM circuit.

2.2 MRR for Single Spark

The material removal rate (*MRR*) is defined as the volume of material removed per unit time. It is calculated by multiplying the volume of material removed in a single spark by the number of sparks occurring in unit time assuming that each of the sparks removes same amount of materials. Thus, the *MRR* is expressed by Eqn. (5) as below.

$$MRR = N_s \times \frac{kCV^2}{2\rho}\left[\frac{k_1}{H_v} + \frac{k_2}{H_m}\right] \tag{5}$$

This is the expression of *MRR* for single spark erosion in RC pulse micro-EDM which shows that the electrical parameters, number of sparks per unit time and thermal properties of the material directly controls the erosion rate.

3 *MRR* for Multi-spark micro-EDM

Effective spark generation depends on many conditions such as the electrical and physical properties of workpiece and tool electrode, flushing conditions, spark gap, depth of the machining [16, 19, 20]. Due to the stochastic nature of micro-EDM, it is difficult to estimate the number of effective sparks theoretically. Therefore, micro-EDM of copper is conducted to investigate the deviation of experimental *MRR* from the *MRR* of ideal conditions. Experiments were accomplished by a multi-purpose miniature machine tool (DT-110, Mikrotools Inc., Singapore) using the machining conditions as given in Table 1. The DOE was done based on two parameters capacitance and voltage of four levels as shown in Table 2.

Twelve experiments based on selected parameters (Table 2) were designed and conducted. Micro-holes were drilled on copper workpiece with 1 mm diameter copper tool electrode using kerosene dielectric fluid. To investigate the material removal mechanism and crater geometry, a SEM micrograph of the machined copper workpiece was captured as shown in Fig. 2. Copper micro-craters are observed to have a clear and identical geometric pattern because of the uniform removal of material by melting and vaporization. The micrograph also showed no cracks on the machined surface and micro-crater is spherical in shape.

Finally, actual volume of the removed material was found by measuring the depth and diameter of the drilled holes. Then *MRR* was then calculated for each of the experiments. The twelve experiments and their corresponding MRR are listed in Table 3. The theoretical *MRR* (Eqn. 5) and experimental actual *MRR* are compared graphically as shown in Fig. 3. It is observed from Fig. 3 that the experimental *MRR* is about half of the theoretical *MRR*. Eqn. (5) has been formulated considering the ideal situation based on a single spark erosion volume. In multi-spark machining, charging and discharging do not follow the estimated time constant and there are many missing sparks among the estimated number of theoretical sparks. As such the number of effective sparks is less than the theoretical number of sparks in micro-EDM which reduces the *MRR* in multi-spark machining condition. Therefore, the *MRR* as expressed by Eqn. (5) is found to be valid for single spark machining only and it is not valid for multi-spark machining for real application in making molds and or other products. However, the single-spark *MRR* expression can be adjusted to use for multi-spark *MRR* purposes. As such based on experimental study as discussed above, Eqn. (5) can be transformed for multi-spark MRR purposes by with a multiplying factor, η as expressed by Eqn. (6). The value of the correction factor would be different for different materials and conditions which would be estimated empirically. In this experimental study of copper workpiece material, the value of the multiplying factor was found to be η = 0.5.

$$MRR_{adj} = \eta \times N_s \times \frac{kCV^2}{2\rho}\left[\frac{k_1}{H_v} + \frac{k_2}{H_m}\right] \tag{6}$$

Table 1. Micro-EDM conditions for copper material [6]

Conditions	Values
Variable parameter	
Capacitance, *C* (nF)	10, 1, 0.22, 0.1
Voltage, *V* (V)	100, 90, 80
Constant conditions	
Specific heat, c_p (J/Kg^{0}C)	390
Melting temperature, T_m (^{0}C)	1084
Boiling temperature, T_b (^{0}C)	2562
Room temperature, T_0 (^{0}C)	20
Latent heat of melting, L_m (J/Kg)	207000
Latent heat of vaporization, L_v (J/Kg)	4730000
Density, ρ (Kg/m^3)	8960
RC circuit resistance, R_1 (Ω)	1000

Conditions	Values
Fraction of energy consumed for material removal, *k (%)*	4.35
Fraction of energy consumed for material removal by melting, k_1	0.11x*k*
Fraction of energy consumed for material removal by vaporization, k_2	0.89x*k*
Dielectric fluid	Kerosene
Cylindrical copper rod tool electrode diameter (mm)	1
Tool polarity	-ve
Feed rate, *f* (μm/s)	0.2
Speed, *n* (rpm)	300

Table 2. Experimental Micro-EDM parameters for *MRR* of copper workpiece

Parameter	Level			
	I	*II*	*III*	*IV*
Capacitance C (nF)	0.1	0.22	1	10
Voltage V (V)	80	90	100	110

Table 3. Theoretical and experimental *MRR* in micro-EDM

	C (nF)	*V* (V)	*MRR* (mm³/s) (Eqn. 5)	MRR_{ex} (mm³/s)	$\frac{MRR_{ex}}{MRR}$
1	10	100	0.001586	0.000726	0.458
2	10	90	0.001285	0.000664	0.517
3	10	80	0.001015	0.000523	0.516
4	1.0	100	0.001586	0.000633	0.400
5	1.0	90	0.001285	0.000603	0.470
6	1.0	80	0.001015	0.000503	0.496
7	0.22	100	0.001586	0.000876	0.552
8	0.22	90	0.001285	0.000790	0.615
9	0.22	80	0.001015	0.000669	0.660
10	0.1	100	0.001586	0.000654	0.412
11	0.1	90	0.001285	0.000510	0.397
12	0.1	80	0.001015	0.000458	0.451

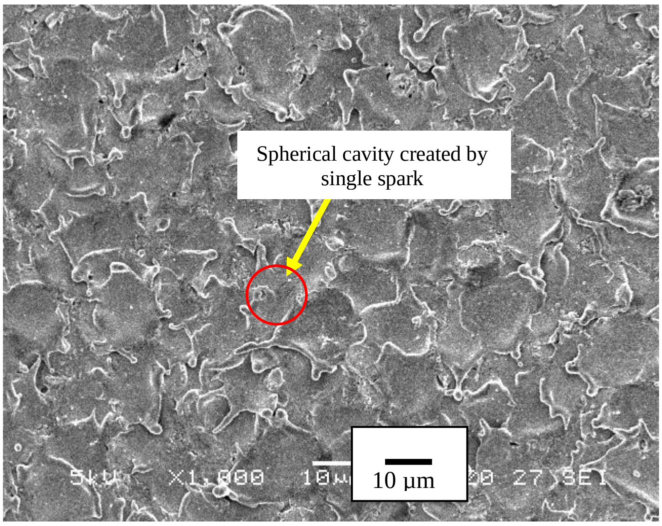

Figure 2. SEM micrograph of surface texture in micro-EDM of copper showing a spherical micro-crater.

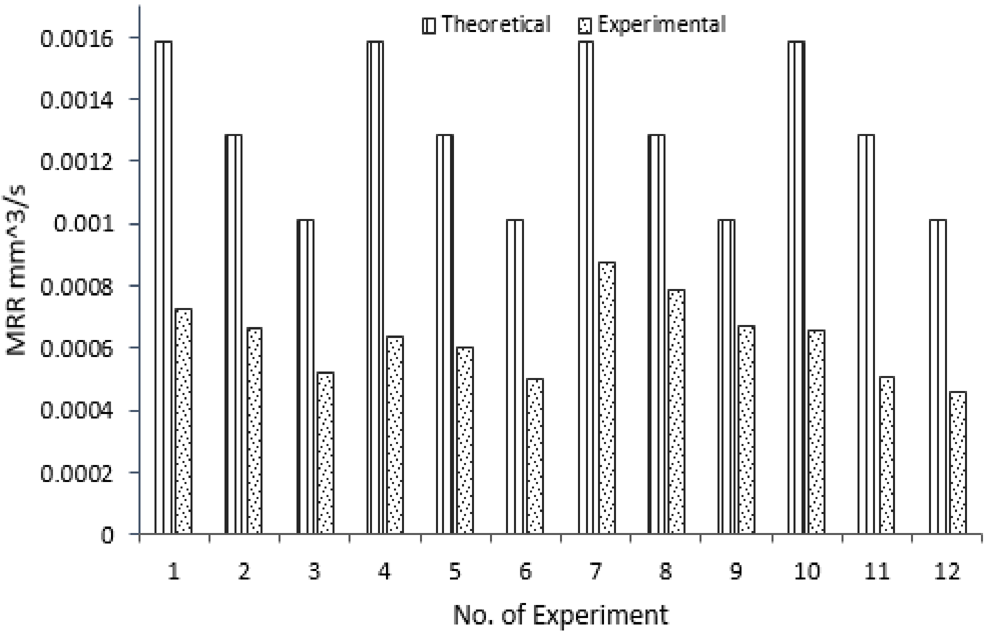

Figure 3. Comparison of theoretical and experimental MRR of micro-EDM of copper

4 Conclusions

In this study, the mechanism of material removal and the MRR for single-spark and multi-spark micro-EDM are compared. MRR due to single spark is formulated based on electro-thermal mechanism. Then during real experimental machining number of sparks and total machining time are counted. The volume of material removal was measured and then converted into MRR. The experiments were repeated many times and a significant difference in MRR due to single-spark and multi-spark micro EDM was observed. The specific findings of this study are as follows:

1. In ideal conditions, number of spark depends on capacitance and resistance. The number of effective sparks is found to be identical with theoretically calculated values at the initial machining stage. However, the frequency of effective discharges decreases with the progress of the machining due to inability of debris flushing.
2. In micro-EDM of copper, it is observed that the experimental *MRR* in multi-spark is almost half of the theoretical *MRR* in single spark. This indicates that the MRR reduces by a higher percentage due to the creation of ineffective pulses in multi-spark erosion. Therefore, a correction factor is needed to adjust in multi-spark erosion.
3. The *MRR* in multi-spark micro-EDM is the function of effective sparks generated in the specified duration which depends on many factors such as the electrical and physical properties of materials, flushing conditions, spark gap, depth of the machining. As an experimental correction factor, it includes all these conditions in estimation of *MRR*.
4. In this experimental study it was found that the correction factor is to be 0.5 for coper workpiece and copper tool electrode (i.e., $\eta = 0.5$ in Equation 6)

Acknowledgements

The authors would like to thank the Ministry of Higher Education of Malaysia (MOHE) for financial support under Research Grant FRGS 14-131-0372.

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