Energy Distribution Ratio into Micro EDM Electrodes*

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Abstract
Energy distribution ratio into micro EDM electrodes was determined based on the summation between the ratio of energy loss due to heat conduction within electrodes and ratio of energy carried away by debris. Ratio of energy loss due to heat conduction was obtained by comparing the measured and calculated temperature rise on electrode after igniting plural pulses discharges. On the other hand, the ratio of energy carried away by debris was calculated based on the measured removal volume. Energy distribution ratio into micro EDM anode and cathode was between 10% and 15% in total which was comparatively lower than that of macro EDM. This is because much larger fraction of the total discharge energy is consumed for the generation and enthalpy increase of the plasma in the early stage of discharge. Besides, unlike macro EDM the energy carried away by debris in micro EDM cannot be ignored compared with the energy lost due to heat conduction. This means, the energy consumption by material removal in micro EDM with regard to the energy distributed into the electrodes is more efficient compared to that of macro EDM.

Key words: EDM, Micro EDM, Energy Distribution, Electrode Temperature

1. Introduction
Electrical discharge machining (EDM) is a material removal process by means of thermal erosion which utilizes electrical discharge energy as the main source. Generally, during EDM process the total electrical discharge energy is distributed into workpiece and tool electrode, and lost into the gap between the electrodes. The energy that is distributed into electrodes is transformed into heat and portion of it erodes both the workpiece and the tool. This fact shows that the distribution of energy into electrodes directly influences tool wear and workpiece removal. The wear and removal of electrodes are the main parameters to determine the accuracy and the efficiency of EDM process. Thus, the energy distribution into electrodes can be considered as an important factor to explain the performances of EDM process. Besides, the result of energy distribution ratio into micro EDM electrodes can be used for further research works regarding the fundamental of micro EDM process such as determination of the plasma diameter, investigation of the energy consumption during removal process and understanding of the electrode deformation due to thermal stress.

Xia et al. [1] and Hayakawa et al. [2] estimated the energy distribution ratio by comparing experimentally measured and calculated temperature rise on Cu electrodes under normal EDM conditions and significantly longer discharge durations, respectively. Based on these reports, ratio of energy distributed into the electrodes in total was significantly higher in the case of longer discharge durations. Hayakawa et al. [2] reported that in the early stage of arc discharge, a large fraction of the discharge power was consumed in the formation of plasma which also means the energy distribution ratio into electrodes can be expected to...
become lower when comparatively shorter discharge durations are used. Furthermore, Xia et al. [1] reported that when discharge durations were shorter than a few tens µs carbon layer which protects the anode surface from wear was not generated and hence the material removal rate was directly related to the energy distribution ratio where the greater values were obtained in the case of anode compared to that of cathode although both electrodes are made of the same material. On the other hand, discharge durations in the case of micro EDM are comparatively shorter than that of macro EDM. Therefore, the energy distribution ratio into electrodes of micro EDM should be lower than that of macro EDM. Additionally, the material removal rate in micro EDM is also expected to rely on the energy distribution ratio due to the short discharge durations.

Method to obtain the energy distribution ratio into electrodes in the case of macro EDM has been reported in [1] and [2]. However, the energy distribution ratio into micro EDM electrodes has never been reported yet. In this work, the similar principle as in [1] and [2] will be used to determine the energy distribution into micro EDM electrodes. Initially, the temperature rise on the Cu electrode will be measured using a thermocouple. Then, the temperature rise on the electrode will be simulated using heat conduction model by assuming an energy distribution ratio into the electrode. The calculation of the temperature rise will be repeated by varying the assumed energy distribution ratio until both measured and calculated results coincided, where the assumed ratio is now equal to the ratio of energy that is lost due to heat conduction within the electrode with regard to the total discharge energy. However, several difficulties are expected in the case of micro EDM compared to the work done in [1] and [2] due to extremely low discharge energy, short discharge durations and no comprehensive information on plasma size. In addition, unlike macro EDM the energy carried away by debris cannot be ignored compared with the energy lost due to heat conduction within the electrode. Hence, the energy distribution ratio into electrode should be determined based on the sum of energy distribution ratio due to the heat conduction into electrode and the heat carried away by debris.

2. Method to determine energy distribution ratio into electrodes

Total discharge energy generated between workpiece and tool electrode is distributed into them and lost within their gap as shown in Fig. 1 (a). As depicted in Fig. 1 (b) the energy that is distributed into the electrodes is then consumed for material removal and carried away by debris, lost by heat conduction within electrodes, and lost due to heat convection and radiation. Hayakawa et al. [2] calculated the heat flux due to convection and radiation at the long discharge duration and found that it is negligibly small and most of the discharge energy is conducted into electrodes. Based on this report, the energy loss due to heat convection and radiation can be ignored and the energy distribution into electrodes is dominated only by the energy loss due to heat conduction within electrodes and the energy carried away by debris. Thus, in this work the energy distribution ratio into electrodes is determined based on the summation of the ratio of energy loss due to heat conduction and the ratio of energy carried away by debris.

![Energy distribution in EDM process](image)

Figure 1: Energy distribution in EDM process
2.1 Principle

The energy loss due to heat conduction within electrode is determined by comparing measured and calculated temperature rise on the electrode, \( T_m(t) \) and \( T_c(t) \), respectively. The measured result is obtained using a thermocouple made of constantan wire and the electrode’s material. Then the temperature rise on electrode is calculated using finite difference method through a physical model which is built using a numerical analysis software i.e. PHOENICS.

As mentioned in §1, short discharge durations and low discharge energy result in several difficulties to determine the energy distribution ratio in the case of micro EDM. For instance, the discharge energy is too small when a single pulse discharge is ignited, where the signal of the temperature rise is too weak and not correctly detectable if the distance of discharge location relative to the thermocouple junction is too long. However, the distance between the measurement junction and discharge location also could not be made too short due to two reasons. First is the thermocouple amplifier is affected by electromagnetic noise due to the electrical discharge. Xia et al. [1] determined energy distribution into macro EDM electrodes by measuring temperature rise at a location more than 1 mm distanced from the discharge location. The result shows that the temperature measurement device only worked well 2 ms after the occurrence of the single discharge due to the electromagnetic noise. If the distance was not sufficiently long the temperature rise may reach its peak within the electromagnetic noise region. Consequently, the temperature peak cannot be measured correctly and unable to be compared with the calculated result which leads to a low reliability of the obtained result. The second reason is plasma diameter in micro EDM process is unknown and therefore the distance between measurement point and discharge location must be made sufficiently long so that the simulation result is not affected by the assumed plasma diameter.

In this work, discharge durations are shorter than 200 ns which are 100 times shorter than the minimum discharge duration that was used in the case of macro EDM in [1]. Thus, the temperature signal of micro EDM is expected to be so weak and may not be detectable if only single pulse discharge is ignited at a location that is too far from the thermocouple junction. On the other hand, the thermocouple amplifier does not work well during discharging period and the simulation result should not be affected by the assumed plasma diameter. As a solution, instead of single pulse, plural pulses discharges must be ignited at a sufficiently long distance from thermocouple junction so that higher discharge energy can be delivered and adequate temperature rise signal and its peak could be measured in the outside region of the electromagnetic noise.

Figure 2 shows a flowchart which indicates a method to determine energy distribution ratio into electrode. Initially, plural pulses discharges are ignited between micro EDM electrodes and temperature rise on the electrode is measured using an oscilloscope. Whilst, other results of experiment i.e. discharge current \( (i_d) \), and discharge voltage \( (u_d) \) will be measured too. Based on the discharge current measurement results, the discharges timing, discharge duration and duty factor can be determined. Then, by using a microscope the distance between discharges location and temperature measurement junction will be measured. These parameters are then used to develop the physical model to calculate the temperature rise on the electrode.

To determine the ratio of energy loss due to heat conduction within electrode, an assumption of distribution ratio, \( X_{con} = \) energy loss due to heat conduction within electrode / total discharge energy, is required. Calculation of the temperature rise on electrode will be repeated by varying the value of \( X_{con} \) until the calculated result coincides with the measured temperature rise which means \( X_{con} \) is now equal to the ratio of energy that is lost due to heat conduction within electrode.
The ratio of energy carried away by debris, $X_{deb} = \frac{\text{energy carried away by debris}}{\text{total discharge energy}}$, is calculated based on the measured electrode removal volume. Cu electrode is machined by igniting more than a million single pulse discharges. The volume of the electrode before and after machining is measured using a microscope to obtain the removal volume. The removal volume per pulse, $V$, is then used to calculate the energy carried away by debris per pulse as follows:

$$E_{debm} = \rho V\left[c(T_m-T_s)+L_m\right]$$  \hspace{1cm} (1)  

$$E_{debv} = \rho V\left[c(T_v-T_s) + L_m + L_v\right]$$  \hspace{1cm} (2)

Where,  
$E_{debm}$ is amount of energy where removal action is by melting.  
$E_{debv}$ is amount of energy where removal action is by vaporization.  
$\rho$: density $= 8880$ [kg/m³], $c$: specific heat $= 386$ [J/(kg K)],  
$T_m$: melting point $= 1084.62$ [°C], $T_v$: boiling point $= 2562$ [°C]  
$T_s$: average temperature of electrode surface in steady state during machining  
$L_m$: the heat of fusion $= 2.05 \times 10^5$ [J/kg], $L_v$: evaporation heat $= 5.03 \times 10^6$ [J/kg]

Figure 2: Determination of energy distribution into electrode

Start  
- Input discharge timing, period and duty factor  
- Measure removal volume due to micro EDM

Assume a distribution ratio due to heat conduction, $X_{con}$

Measure temperature rise on electrode, $T_m(t)$ 
- Input power $X_{con}i_cu_c$ into electrode

Calculate temperature rise on electrode, $T_c(t)$ 

Determine the energy distribution ratio into electrode:

$$X = X_{con} + X_{deb}$$

End
In macro EDM, although the energy carried away by debris from workpiece and tool electrode in total was assumed at maximum (debris was removed at the boiling point only), it was less than 3% of the total discharge energy [4]. On the other hand, more than 60% of the total discharge energy was lost due to heat conduction within the electrodes [4]. This means the ratio of energy carried away by debris is significantly lower than that lost due to heat conduction within electrodes. However, in micro EDM, the plasma diameter is in the initial stage of development due to the short discharge duration leading to extremely high power density. Since high power density results in high removal efficiency, the energy carried away by debris cannot be ignored. However, the removal mechanism either dominated by melting or vaporization is also unknown. Therefore, in this work a removal mechanism index, $g$ ($0 \leq g \leq 1$) will be used to estimate the range of $X_{deb}$ as follows:

$$X_{deb} = \frac{1 - g}{E_{deb}} + g \cdot E_{deb} / (i_e \cdot u_e \cdot L_e) \text{ ... (3)}$$

Noted from Eq. (3), when $g$ is equal to 0 and 1 the removal process is accomplished only by melting and vaporization, respectively. The polarity of the electrode during machining indicates the determination of energy ratio carried away by debris is for anode or cathode. Finally the energy distribution ratio into electrode can be calculated as follows:

$$X = X_{con} + X_{deb} \text{ ... (4)}$$

### 2.2 Experimental setup for temperature measurement

There were two different types of workpiece’s geometry which were used in the experimental setup for temperature rise measurement in this work. Figures 3 and 4 show the setup for Cu foil workpiece and Cu wire workpiece, respectively. The setup with Cu foil workpiece allows plural pulses arc to be ignited at a closer distance relative to the thermocouple junction compared to that of Cu wire workpiece, where the minimum distance was only separated by the foil thickness i.e. 50 µm as shown in Fig. 3 (b). However, the number of plural pulses was limited otherwise the Cu foil workpiece could be penetrated.

The experiment began by manually approaching a Cu tool towards the Cu workpiece until plural pulses arc were ignited. The plural pulses arc were produced by relaxation (RC) pulse generator which was composed of a DC power regulator, a 1 kΩ resistor and a capacitor. The temperature rise signal was amplified using a thermocouple amplifier (AD594A) which was installed inside a steel shieldbox to reduce the effect of electromagnetic noise from surrounding. The amplified signal was then sent to an oscilloscope. The distance between discharges location and thermocouple junction was then precisely measured using a microscope.

![Figure 3: Temperature measurements on Cu foil workpiece](image)
2.3 Temperature rise calculation model

Figures 5 and 6 show physical models which were developed using PHOENICS in order to calculate the temperature rise within Cu foil and Cu wire workpiece, respectively. The Cu foil was modeled as a thin circular foil with \( \Phi 12 \) mm in diameter and 0.05 mm in thickness. Calculation area for the Cu foil was smaller than the actual size of 20 mm in diameter because temperature did not change during the measurement time in the outside region. Therefore, it was assumed that the circumferential boundary remains at room temperature. A constantan wire with \( \Phi 0.10 \) mm in diameter and 0.75 mm in length was attached at the bottom-centre of Cu foil. Although the actual length of the constantan wire was longer than 50 mm, it was sufficient to set 0.75 mm within the model because calculation results showed no temperature change beyond this point.

On the other hand, Cu wire workpiece was modeled similar to the actual size, where the diameter and length was \( \Phi 0.3 \) mm and 5.0 mm, respectively. As shown in Fig. 6, the distance between discharges location and constantan wire, \( a \) and the length of the constantan wire that was in contact with the Cu wire, \( b \) was modeled according to the result of measurement using a microscope, where the range of \( a \) and \( b \) was 0.5 mm to 1.0 mm and 0.7 mm to 1.3 mm, respectively. Although the actual length of constantan wire which was connected to the thermocouple amplifier was longer, it was set 1.7 mm within the model because calculation results showed no temperature change beyond this point within the calculation period.

The output of the thermocouple is determined by the temperature at the interface between the constantan wire and the Cu wire. However, the temperature is not uniform along the axis of the Cu wire. Hence, the output of the thermocouple indicates the average along the interface. Therefore, the measured temperature should be compared with the average of the temperature distribution calculated at the interface.

All the Cu electrode and constantan wire surfaces within the analysis domain were assumed adiabatic except at discharge locations and the thermocouple junction. Arc column diameter was assumed to be constant and equal to the average crater size based on measurement using a microscope. Since, the actual size of discharge arc in micro EDM has never been reported, the sensitivity of calculation result with regard to the assumed arc diameter was investigated. The actual size of constantan wire diameter was not so different compared to the size of Cu foil thickness and Cu wire diameter which were used as workpieces in this work. Hence, heat conduction within the constantan wire was expected to be significant. Thus, constantan wire was also included in the calculation model.
3. Results and discussions

3.1 Preliminary test

In order to increase the reliability of the result, temperature rise on Cu wire was measured at two different locations. Figure 7 shows the comparison of measured and calculated temperature rise at 1.59 mm and 0.88 mm distance between thermocouple junction and discharges location. As shown in the figure, the measured temperature rise coincides with the calculated one when the ratio of energy loss due to heat conduction, $X_{\text{con}}$, was assumed approximately 3% in both cases. This means no energy is lost within the distance between both locations, and thus the ratio of energy that is lost due to conduction within electrode is not sensitive to the relative distance between discharges location and thermocouple junction.

Due to low discharge energy and significantly short discharge durations in micro EDM, about 20 to 50 and more than 1000 discharges were ignited under each experiment for temperature rise measurement in the case of Cu foil and Cu wire, respectively. When igniting single pulse discharge on Cu foil the correct temperature signal was undetected. Figure 8 shows the comparison of measured and calculated temperature rise on the Cu foil when a single pulse discharge was ignited in micro EDM. As shown by solid line in the figure, instead of temperature rise only the effects of electromagnetic noise were recorded by the oscilloscope within the measurement period. The measured signal was compared with the calculated result by assuming the $X_{\text{con}}$ was equal to 5%. In the figure, the calculated temperature reaches its peak before 0.1 ms of the measurement time (15 µs after discharge) and gradually dropped. Moreover, the temperature rise calculated was only one degree at the peak. Thus, comparison of measured and calculated temperature rise could not be done successfully by igniting a single pulse discharge in micro EDM.
3.2 Ratio of energy loss due to heat conduction within electrodes

In this section the ratio of energy loss due to heat conduction within electrodes will be discussed. Measured and calculated temperature rise on Cu foil and Cu wire obtained from plural pulses discharge is shown in Fig. 9 (a) and (b), respectively. In the case of Cu foil anode in Fig. 9 (a), by assuming that the plasma diameter was equal to the measured crater size and constant during discharge duration, calculated result at 5% of the total discharge energy coincided well with the measured result approximately after 0.7 ms measurement time.

Figure 8: Measured and calculated temperature rise for single pulse in micro EDM

Figure 9: Measured and calculated temperature rise

As shown in Fig. 9 (a), from 0.03 ms to 0.7 ms, there was inconsistency between calculated and measured results. Discharges were ignited 41 times approximately from 0.03 ms to 0.36 ms, and during this discharging period the inconsistency between results was caused by the electromagnetic noise, and the later inconsistency was due to the malfunction of the amplifier which was unable to work well just immediately after the overrange load was removed. When the polarity of the Cu foil was changed to negative, the $X_{con}$ was equal to 2.5% and this means the ratio of energy loss due to heat conduction into cathode was 2.5% of total discharge energy.

However, as shown in Fig. 9 (a) the calculated temperature rise reached the peaks before the thermocouple amplifier started to work well. The measured and calculated temperature gradient could be compared only at the time sufficiently long after the plural pulses discharges, and this leads to low reliability of the results. The main reason was the distance between thermocouple junction and discharges location not sufficiently long. Owing to this short distance, the calculation result was also affected by the assumed plasma diameter. Figure 10 shows the effect of assumed plasma diameter on temperature rise calculation. In Fig. 10 (a), when plasma diameter was assumed 10 times of crater diameter (100 µm) in the case of Cu foil, the calculation result became higher than that of 10 µm plasma diameter.

To increase the reliability of the results, more discharge arcs were ignited at longer distances relative to the thermocouple junction by using Cu wire as a workpiece. As shown in Fig. 9 (b), calculated results at $X_{con}$ approximately 6% and 3% coincided with the measured temperature rise on anode and cathode, respectively. As shown in the figure, the measured and calculated temperature peaks could be compared and this indicates the reliability of the result was better than that of Cu foil. Furthermore, as shown in Fig. 10 (b) the calculation result was not affected by the assumed plasma diameter. This also results from sufficiently long distance between discharges location and thermocouple junction.

In both cases of Cu foil and Cu wire workpiece, there was no significant difference with
regard to the obtained distribution ratio of energy loss due to heat conduction within electrodes. The slight difference of the ratio may be caused by the assumption of the plasma diameter in the case of Cu foil during temperature rise calculation. This means the result obtained in the case of Cu wire was reliable.

### 3.3 Ratio of energy carried away by debris

The ratio of energy carried away by debris was calculated based on electrodes removal volume by using Eqs. (1) ~ (3). During electrodes removal process more than 1 million and 10 millions discharges were ignited on anode and cathode, respectively. The RC discharge circuit with 1000 pF capacitor and 100 V open circuit voltage was used, where the generated arc was approximately; peak current = 1.8 A, and discharge duration = 70 ns.

The ratio of energy carried away by debris with regard to the removal mechanism index, \( g \) is shown in Fig. 11. The energy carried away by debris is minimum if the removal mechanism is based on melting by 100\% (\( g = 0 \)). On the contrary, if the removal is solely due to vaporization (\( g = 1 \)) the energy carried away by debris is maximum. This is based on the fact that more energy is consumed when accompanied with vaporization. Experimental results indicate that the removal volume per pulse in the case of anode was 1.9008 μm\(^3\) and approximately 10 times larger than that of cathode. Thus, the value of \( X_{\text{deb}} \) is significantly higher in the case of anode than that of cathode as shown in Fig. 11. With regard to \( 0 \leq g \leq 1 \), \( X_{\text{deb}} \) ranged from 0.57\% to 4.78\% and 0.06\% to 0.48\% for anode and cathode, respectively. It is noted that \( X_{\text{deb}} \) is not negligibly small compared with \( X_{\text{con}} \) in micro EDM. This is because the power density of micro EDM plasma is significantly high.

![Figure 11: Ratio of energy carried away by debris](image)

### 3.4 Energy distribution ratio

Total discharge energy in micro EDM process is distributed into workpiece and tool electrode, and lost into gap. It was known in the previous sections that the energy distributed into electrodes was dominated by the energy lost due to heat conduction and the energy carried away by debris. Therefore, it is sufficient to consider only the summation of the ratio of energy that is lost due to heat conduction and the ratio of energy carried away by debris as the energy distribution ratio into electrodes. The range of the ratio with regard to the removal mechanism index, \( g \) is shown in Fig. 12. As shown in the figure the energy distribution ratio into anode is greater than that of cathode and the ranges are 6.6\% to 10.8\% and 3.3\% to 3.7\%, respectively. Figure 13 shows the overall energy distribution ratio during micro EDM process. The energy distribution ratio into anode and cathode in total is between 10\% and 15\%. This means at least 85\% of total discharge energy was first lost into gap.
The relationship between discharge durations and energy distribution ratio into electrodes in total is shown in Fig. 14. Xia et al. [1] reported that under normal EDM conditions 65% of total discharge energy was delivered into electrodes in total. Hayakawa et al. [2] used significantly longer discharge durations and found that almost all discharge energy was distributed into anode and cathode. The energy distribution ratio into electrodes obtained in this work was comparatively lower than that was reported in [1] and [2], and the good correlation between the ratio and discharge durations can be observed in Fig. 14. Based on the idea reported in [2], the result measured in micro EDM indicates that much larger fraction of the total discharge energy is consumed for the generation and enthalpy increase of the plasma than in macro EDM, because discharge durations are significantly short.

![Figure 12: Energy distribution ratio into electrodes vs. discharge durations](image1)

![Figure 13: Energy distribution during micro EDM process](image2)

![Figure 14: Total energy distribution ratio into electrodes vs. discharge durations](image3)
4. Conclusions

In this work a method to determine energy distribution ratio into micro EDM electrodes was explained. Total discharge energy distributed into electrodes was dominated by the energy loss due to heat conduction and the energy carried away by debris. The ratio of energy lost due to heat conduction was determined by comparing the measured and calculated temperature rise on electrode. On the other hand, the ratio of energy carried away by debris was calculated based on the measured removal volume from electrode. From this work the following conclusions can be drawn:

1) Plural pulses discharges must be ignited at sufficiently long distance relative to the thermocouple junction so that temperature peak could be measured and compared with the calculated temperature rise in order to increase the reliability of the result.
2) The ratio of energy loss due to heat conduction which was obtained using Cu wire is more reliable than that of Cu foil because the temperature peak could be measured, eliminating the effect of electromagnetic noise.
3) Furthermore, measurement accuracy using Cu wire was better because the calculation result was not influenced by the assumed plasma diameter. However, there was no significant difference in the obtained ratio between the case of Cu wire and Cu foil, meaning the result obtained in the case of Cu wire was correct.
4) The energy distribution ratio into micro EDM Cu electrodes was significantly lower than that of macro EDM. This indicates that, the significantly short discharges durations of micro EDM leads to a much larger fraction of the total discharge energy to be consumed for the generation and enthalpy increase of the plasma than in macro EDM.
5) The result that energy distribution ratio into anode was higher than that of into cathode is consistent with macro EDM.
6) The energy carried away by debris is not negligibly small compared with the energy loss due to heat conduction within the electrodes of micro EDM. This is because the power density of micro EDM plasma is significantly high.

References