Improving Discharge Energy in Micro-EDM with Electrostatic Induction Feeding by Controlled Pulse Train Method

Norliana Mohd Abbas, Masanori Kunieda

* Department of Precision Engineering, The University of Tokyo, Tokyo 113, Japan

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Abstract

Micro EDM with electrostatic induction feeding method can stimulate minimum discharge energy per pulse. With this pulse generator, since there is no contact between the pulse power supply and the tool, the tool electrode can be rotated at very high speed and significantly improve the cooling of the tool electrode. However, since the feeding capacitance which is formed between the feeding electrode and tool electrode is extremely small, it is difficult to conduct rough machining. Therefore, controlled pulse train method is introduced to increase the discharge energy. With this method, discharge energy can be enlarged even if the machining is done with the same small capacitance. Results show that material removal rate (MRR) can be increased with the increase in pulse train duration and higher MRR and lower tool wear ratio (TWR) can be achieved compared to the conventional method.

Key words: Micro EDM, electrostatic induction feeding, controlled pulse train method, frequency, discharge energy

1. INTRODUCTION

Micro electrical discharge machining (EDM) is widely used in drilling small and deep holes for example in the application of turbine components or fuel injection nozzle [1-3]. In order to avoid localized discharge and abnormal arc, flushing is done by rotating the tool electrode. By rotating the spindle at very high speed up to 50,000 rpm debris can be flushed effectively, electrode surface temperature can be decreased and higher discharge frequency can be realized [4]. In micro EDM, mostly relaxation pulse generator is utilized because low discharge energy and short pulse duration can easily be achieved. However, since the power supply must be connected to the tool electrode using a brush, the spindle cannot be rotated at very high speed because it can cause vibration and may influence the machining accuracy. Using the electrostatic induction feeding method as a pulse generator, tool electrode rotation speed can be increased significantly because there is no contact between the rotating tool electrode and electric feeder [5-7]. Circuits for both generators are shown in Fig. 1. For electrostatic induction feeding, capacitance \( C_f \) which is formed in the gap between the feeding electrode and tool electrode holder is significantly small and insufficient to machine with high material removal rate (MRR).

Thus, the idea of the controlled pulse train method was introduced by Niwa [5] to overcome this problem. With this method, since high frequency AC pulse discharge is maintained without interruption within a fixed pulse train duration, higher discharge energy can be achieved even if the same small capacitance is used. However, Niwa [5] only proposed the above idea, but did not show any machining results or current waveforms to verify the occurrence of continuous AC discharges. Yahagi et al. [8] found that larger craters can be obtained from the pulse train method. However, machining was difficult with this method because the frequency of the AC pulse voltage used in their work was not sufficiently high for AC discharge to continue without interruption within the pulse train duration. Moreover, the duration of the AC discharge was not constant because discharge ignition is usually delayed when AC voltage is applied to the gap with constant duration. Li et al. [9] developed a multi-mode pulse power supply in order to obtain different ranges of energy. Five pulses of high frequency voltage were supplied intermittently with a regular cycle. The objective was to achieve high discharge current and short discharge duration in order to improve surface roughness and machining efficiency of array micro holes. However, the purpose of this method is different from the present work where AC pulse discharge continues to occur at the same spot.

Based on the preliminary study on the principle of the pulse train method by Niwa [5] and Yahagi et al. [8], this paper developed a new circuit for the controlled pulse train method where the discharge ignition is detected to keep the pulse train duration constant. Then, controllability of material removal at
each discharge crater with this method investigated under different pulse train duration and pulse voltage frequency.

2. CONTROLLED PULSE TRAIN METHOD

In electrostatic induction feeding, the feeding capacitance $C_1$ determines the discharge energy and discharge duration [10,11]. When machining is done at low pulse frequency, since there is enough time for dielectric strength to recover, the bipolar discharge current can occur at every half cycle. This causes the craters to be scattered at different locations after every discharge. This condition is illustrated in Fig. 2a. Increment in MRR can be done by increasing the frequency of the pulse power supply because this will elevate the discharge frequency. However, if the frequency is increased further, discharge cannot occur during half cycle of the pulse as shown in Fig. 2b. This is because discharge is ignited after a discharge delay time and the average discharge delay time depends on the gap width and contamination in the gap which statistically obeys the exponential distribution [12]. On the other hand, if the pulse frequency is increased further, there will be no interval time sufficient for the dielectric breakdown strength to recover. Once discharge is ignited, very large crater will be generated at only one location which is actually damaging the machined surface as presented in Fig. 2c. This is an undesirable condition.

In this paper, therefore the controlled pulse train method illustrated in Fig. 3 is proposed. The idea was realized by adding one shot multivibrator and switching circuit to the machining system as shown in Fig. 4. In this method, high frequency voltage is intermittently supplied to the gap. Once discharge ignites, it is detected by the current sensor. The current sensor then sends a signal to one shot multivibrator circuit to allow discharges to continue within a controlled pulse train duration. The pulse train is a group of discharges which is allowed to occur within a pre-determined time. With this, number of discharges can occur at the same location. After the end of the pre-determined time, a signal is sent to the switching circuit to stop the pulse power supply within a predetermined time which is called pulse train interval. During this time, dielectric strength can be recovered. After that, the pulse power supply is switched on again. Then the cycle is reiterated. The next discharge can occur at different location. Hence, higher discharge energy and larger crater size than that generated by individual pulse discharge using the conventional method can be obtained even with a small feeding capacitance $C_1$.

Although Niwa [5] and Yahagi et al. [8] proposed the pulse train method with the pulse interval between the discharges, the pulse train duration was not controlled. On the other hand, since the pulse train duration and pulse interval are controlled to be constant with this method, better material removal and uniform crater size can be achieved.
3. SIZE OF DISCHARGE CRATERS

In the conventional electrostatic induction feeding method, size of discharge crater is influenced by discharge energy per pulse. However, in this study, size of crater is determined by discharge energy per pulse train. In investigating the diameter of discharge craters, machining conditions shown in Table 1 were used. For simplicity, this experiment was done by adding a capacitor to the circuit and the current was supplied using a brush to the tool electrode rotating at 3000 rpm. Panasonic (MG-ED72) μ-EDM machine was utilized in conducting the machining. The voltage and current during the machining were monitored using Tektronix DP 4104 Digital Phosphor Oscilloscope and Tektronix Tek CT-1 current probe. Scanning electron microscope (SEM) was used to capture the image of machined surface. An area was selected randomly and magnified, and craters within the area were measured.

Table 1 Experimental conditions in investigating size of discharge crater

| Pulse power supply | Amplitude (V) | Frequency (MHz) | Feeding capacitance, $C_1$ | Electrode | Workpiece | Dielectric | Pulse train duration (ns) | Pulse train interval (ns) |
|--------------------|---------------|----------------|----------------------------|------------|-----------|-------------|--------------------------|--------------------------|
|                    | 100           | 3, 5           | 470 pF                     | Tungsten carbide | Stainless steel | EDM oil | 50, 300, 900, 1400       | 4600                     |

Fig. 5 shows the comparison of surfaces machined with frequencies of 5 MHz and 3 MHz and pulse train duration of 300 ns and 1400 ns. Fig. 6 shows the relationship between diameter of craters and pulse train duration at two different frequencies. Under the same pulse train duration, crater size with 5 MHz was larger than 3 MHz because number of discharges within the pulse train duration was larger. With 5 MHz, as the pulse train duration increased, diameter of craters was enlarged. This is because discharges occurred continuously at a single spot during the period of the pulse train and number of discharges per pulse train increased with increasing the pulse train duration. For machining with 3 MHz however, there was only a slight increase in crater size as the pulse train duration increased.

To identify the reason why there was only slight increase on crater size with frequency of 3 MHz, observation on discharge current waveforms was done. Fig. 7 shows the comparison between discharge current within the same pulse train duration of 900 ns for 3 MHz and 5 MHz. It is found that, interval between the discharges is longer at 3 MHz than 5 MHz. Hence, discontinuity of discharges during the pulse train duration tends to take place more often with 3 MHz. This is because, with $C_1 = 470$ pF, the duration of individual discharge was 50 ns, which is much shorter compared to the half cycle of the 3 MHz pulse (167 ns) as shown in Fig. 8. Thus, lower frequency results in longer interval between individual pulse discharge. This leads to deionization of the plasma and causes the interruption of discharges within the pulse train duration.

4. CONTINUABILITY OF DISCHARGES WITHIN PULSE TRAIN DURATION

As described in the previous section, it was found that number of discharges per pulse train duration was not constant. This condition is undesirable because it will affect the size of discharge crater. Thus, investigation on the sustainability of discharges was done by identifying the number of discharges occurred continuously within pulse train durations. 100 pulse trains with number of discharges equivalent to about 15 pulse cycles were sampled for pulse frequencies of 3, 5 and 10 MHz. Fig. 9 illustrates the discharge occurrence at respective frequencies. There are lags in a total of about 400 ns to activate the one shot multivibrator circuit and to stop the pulse power supply. During these times, discharge can continue to occur. This is the reason why 15 discharges can be generated at the selected pulse train duration. For the experiment, machining conditions as in Table 1 were employed.

The result as presented in Fig. 10 revealed that number of discharges per pulse train is higher at...
higher frequencies. This is maybe because discharge is able to sustain within the pulse train duration since the interval between the discharges is shorter at higher frequencies. Therefore, when discharge is ignited, it can maintain within the predetermined time until the pulse power supply is stopped. In the case of 3 MHz, the interval between discharges leads to discontinuation of discharges within the pulse train duration. This result verifies the fact that the discharge crater did not increase with increasing the pulse train duration at 3 MHz in Fig. 6.

![Discharge waveforms at pulse train duration of 900ns](image)

**Fig. 7** Discharge waveforms at pulse train duration of 900ns

![Incomplete discharge waveforms at 3MHz and 900ns pulse train duration](image)

**Fig. 8** Incomplete discharge waveforms at 3MHz and 900ns pulse train duration

![Discharge occurrence at various frequencies](image)

**Fig. 9** Discharge occurrence at various frequencies

5. INCREASE OF MATERIAL REMOVAL AT ONE DISCHARGE CRATER

With the controlled pulse train method, as the crater size can be enlarged with the increase in pulse train duration, it is also important to investigate the increment in MRR. In this investigation, comparison between the conventional electrostatic induction feeding method and controlled pulse train method is done using the same feeding capacitance $C_1$. The machining conditions for both methods are presented in Table 2. Since the servo feed system was not yet developed, the maximum MRR was obtained by increasing the feed speed. This is because, MRR can be increased by increasing the set feed speed due to the increment of discharge frequency. However, beyond the feed speed limit machining is not possible, because when the feed speed is higher than MRR, the tool will collide with the workpiece surface and machining cannot continue. With this method, maximum MRR can be obtained.

For the conventional method at first, a frequency was selected and machining was done by increasing the feed speed at that particular frequency until the maximum MRR is reached. Then, another frequency was selected and the process was reiterated. For the controlled pulse train method, machining was done with frequency of 5 MHz by varying the duty cycle with the total cycle time kept constant at 7400 ns. Fig. 11 shows the illustration of the experimental method for the controlled pulse train method. The triangles represent number of discharges which can be generated at every pulse train duration. First, with 400 ns pulse train duration, the machining was done by increasing the feed speed. After the maximum feed speed was obtained, the machining continued with the
other value of pulse train duration and the process was repeated. Finally, the maximum MRRs obtained from every frequency (in the case of conventional method) and every pulse train duration (in the case of controlled pulse train method) were plotted in the graphs shown in Fig. 12 and Fig. 13, respectively.

For conventional method, the MRR peaks at frequency equal to 2 MHz. This is because discharge delay time is necessary for discharge to ignite. At high frequency, the pulse duration becomes shorter than the discharge delay time. This is why discharge cannot occur at every half cycle of the pulse, causing reduction in MRR. In addition, due to incomplete deionization and contamination in the gap during continuation of high frequency discharge, arcing pulses occurred. The arcing pulses does not help in removing the workpiece. Hence, this lead to the reduction in MRR.

On the other hand, in the controlled pulse train method, the duration of the high frequency discharge is controlled and followed by a preset pulse train interval. The pulse train interval allows sufficient time for the recovery of dielectric breakdown strength and removal of the gap contamination. Thus, using the same feeding capacitance $C_1$, the MRR for controlled pulse train method was two times higher than the conventional method as shown in Fig. 13.

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**Table 2 Experimental conditions for investigation on maximum limit of MRR**

| Pulse power supply (V) | 100 |
|------------------------|-----|
| Feeding capacitance, $C_1$ | 470 pF |
| Electrode | Tungsten carbide ($\Omega = 250 \mu m$) |
| Workpiece | Stainless steel (SUS 304) |
| Machining time (s) | 120 |
| Conventional method Frequency (MHz) | 0.5, 1, 2, 3 |
| Controlled pulse train method Frequency (MHz) | 5 |
| Cycle time (ns) | 7400 |
| Pulse train duration (ns) | 400, 1100, 2000, 2800 |

**6. COMPARISON ON ENERGY EFFICIENCY**

With the conventional electrostatic induction feeding method, energy per individual discharge is determined by the feeding capacitance $C_1$, and the material removal is proportional to the total number of discharges. However, with the controlled pulse train method, since the individual discharges continue to occur at the same location, material removal per individual discharge may be different from the conventional method. To investigate this, machining was done at the same total number of discharges. With the controlled pulse train method, 7 discharges were generated within 300 ns pulse train duration followed by 4600 ns pulse train interval at frequency of 5 MHz. In order to obtain the same number of discharges within the same period with the conventional electrostatic induction feeding method, frequency of 700 kHz was used during machining. The machining conditions are given in Table 3 and illustration of the experimental method is shown in Fig. 14.

**Table 3 Experimental conditions to investigate material removal per discharge**

| Pulse power supply (V) | 100 |
|------------------------|-----|
| Feeding capacitance, $C_1$ | 470 pF |
| Electrode | Tungsten carbide ($\Omega = 250 \mu m$) |
| Workpiece | Stainless steel (SUS 304) |
| Machining time (s) | 120 |
| Conventional method Frequency (kHz) | 700 |
| Controlled pulse train method Frequency (MHz) | 5 |
| Pulse train duration (ns) | 300 |
| Pulse train interval (ns) | 4600 |
6.1 Rate of Material Removal

The removal rate was obtained by dividing the volume of material removal with machining time. Fig. 15 shows that the maximum feed speed for the conventional method was 0.9 μm/s while the maximum feed speed for the controlled pulse train method was 1.4 μm/s. Above the feed speed limit, machining was not possible due to short circuit. At the same feed speed, the material removal rate should be the same. However, with the conventional method, as the feed speed increased the tool wear also increased. This is the reason why the material removal rate was higher with the controlled pulse train method under the same feed speed.

The increase in feed speed enhances the discharge frequency. However, this leads to unstable machining and brings to the limit of the feed speed in the conventional method. This is because, during the high feed speed the discharge occurs continuously at every half cycle of the pulse and the interval time between the individual discharges is insufficient for plasma to extinguish. On the other hand, with controlled pulse train method, sufficiently long pulse train interval was fixed after every accumulation of discharges. Thus, the machining was stable leading to higher MRR.

6.2 Tool Wear Ratio (TWR)

The TWR was obtained by dividing the volume of tool wear with the removal volume of workpiece. The result in Fig. 16 shows that under the same feed speed, tool wear ratio was lower with the controlled pulse train method. In the conventional electrostatic induction feeding method, the discharge with a high peak current within short duration in alternating polarity caused high tool wear [13]. However, rapid alternate discharging over a long period of time in oil dielectric with the pulse train method leads to carbon deposition on the tool surface, preventing excessive wear.

6.3 Machined Hole and Machined Surface

The diameter of machined hole and the average crater size for the controlled pulse train method were 264.14 μm and 11.52 μm while for the conventional method were 262.05 μm and 7.57 μm, respectively, as shown in Fig. 17. Larger crater size can be achieved when the controlled pulse train method is employed because discharge occurs continuously at the same spot during pulse train duration.

7. CONCLUSIONS

The controlled pulse train method is an alternative way to increase discharge energy and enlarge unit removal per discharge when there are limits in the design of the equipment and in addition material removal rate cannot be increased infinitely by increasing the frequency. With this method, since discharges occur at single location, larger diameter of craters can be obtained at higher frequency and longer pulse train duration. MRR increased steadily with the increase in pulse train duration when the controlled pulse train method was used. Thus, it is considered that this method can improve the MRR of non-contact electric feeding method using a high speed spindle, where the feeding capacitance in the gap is small. It was also verified that higher MRR and lower TWR can be obtained with the controlled pulse train method as compared to the conventional electrostatic induction feeding method when machining is done under the same discharge energy per unit time.
Controlled pulse train method

Conventional method

|   | a. Diameter: 264.14 μm | b. Average crater size: 11.52 μm | c. Diameter: 262.05 μm | d. Average crater size: 7.57 μm |
|---|-----------------------|-------------------------------|-----------------------|-------------------------------|

Fig. 17 Comparison on diameter and machined surface at the same total discharge energy

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