Development of Electrostatic Induction Feeding EDM with Controlled Pulse Train Method

その他のタイトル	パルス列制御による静電誘導給電放電加工の開発
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論 文 の 内 容 の 要 旨

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(パルス列制御による静電誘導給電放電加工の開発）

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Electrostatic induction feeding method (EIFM) is a pulse generator developed for micro electrical discharge machining (EDM). With EIFM, localized discharge and abnormal arc is less likely to happen because only one discharge can occur in every half cycle of the pulse power supply. Hence, stable machining can be achieved compared to the relaxation pulse generator or RC circuit which is widely used in industry. In micro EDM, tool is rotated to flush the debris in the gap. High speed tool electrode rotation helps in cooling the tool electrode surface. As a result, material removal rate (MRR) increases with increasing the speed of the tool electrode rotation. In RC circuit however, brush is used to connect the power supply to the tool electrode. Thus, it is not possible to rotate the tool at very high speed because it can cause vibration. With EIFM instead, non-contact electrical feeding can be realized and enables the tool to be rotated up to fifty thousand rpm without vibration. However, the material removal is extremely small because of the small capacitance, C_1 which is formed in the gap between the feeding electrode and the tool. This results in very small discharge energy per pulse and insufficient to conduct rough machining. By aiming to achieve a complete machining process: from roughing to finishing using the same pulse generator with non-contact electrical feeding, controlled pulse train method (CPTM) is introduced to overcome the problem,

In micro EDM using EIFM, the use of low pulse frequency between 0.2-1MHz during machining allows sufficient time for dielectric strength to recover and to promote machining stability. MRR can be increased by increasing the frequency. However, by increasing the frequency, there is limit of maximum material removal. Through an experiment, it was proven MRR cannot be increased infinitely by increasing the pulse frequency. Thus, CPTM is proposed since there is a limitation in increasing the discharge energy in conventional EIFM. With CPTM, once discharge occurs, the high frequency discharge is allowed to continue within a controlled pulse train duration. Thus, with the same feeding capacitance $C_{1,}$ larger diameter of craters can be obtained at higher frequency and longer pulse train duration compared to the conventional EIFM where individual pulse discharge was generated. A preliminary study was performed to investigate the feasibility of the idea of CPTM. The results show that discharges generated within pulse train duration can be accumulated at the same location. In addition, discharge energy can be controlled and the diameter of discharge craters increases with increasing the pulse train duration.

With CPTM, it is believed that the discharges are concentrated at a single location because there is no sufficient time for the dielectric strength to recover during high frequency discharge within the pulse train duration. Furthermore, the average diameter of craters increases with the increase in pulse train duration. With the availability of transparent conductive materials, observation of EDM gap was performed using a high-speed video camera from the direction normal to the discharge surface. Light emission from a discharge spot was recorded for every pulse discharge. From the observation, it was confirmed that a number of discharges generated with alternating polarity during the pulse train duration are localized at the same spot. However, during the observation it was found that some discharges are dispersed even if the machining was performed with CPTM. This phenomena occurs because of discharge delay time within the pulse train duration. In addition, interrupted discharges within the pulse train duration caused the long interval between discharges even if the pulse frequency is continuously applied. Hence, an investigation on the interval time that leads to plasma extinction was performed. As a result, it was found that discharge can stay at the same location at least when the interval time is 280ns. The threshold of deionization in micro EDM is about 5 times shorter than in macro EDM.

With CPTM, since number of discharges can occur at a single location, larger diameter of craters can be obtained at higher frequency and longer pulse train duration. The MRR increased steadily with the increase in pulse train duration. It was also verified that the MRR is about 1.7 times higher with CPTM compared to the conventional EIFM when machining was performed under the same discharge energy per unit time. This shows that there is enough time for the dielectric strength to recover after every accumulation of discharges. In the case of conventional EIFM, discharge occurred continuously at every half cycle of the pulse during the high feed speed. This led to insufficient time for plasma to extinguish during the interval time between the individual discharges which results in unstable machining.

Discharge energy can be increased with increasing open voltage, u_o and capacitance, C_1. Since the impedance in the circuit is minimum when machining is performed at the resonant frequency, f_r of the circuit, the u_o can be increased thus increasing the average discharge energy per pulse can be increased. The pulse discharge current can be amplified, thereby discharge continuity within the pulse train duration was improved resulting in largest diameter of discharge craters and highest MRR. At selected capacitance and inductance, the resonant frequency was calculated and machining was performed. The discharge waveforms at the calculated frequency and frequency higher and lower than that were saved. It was found that, at frequency lower than the f_r, the amplitude of discharge current is lower. When the frequency is higher than the f_r, the amplitude of discharge current slightly decreased.Then, the average discharge energy per pulse were calculated from the generated discharge waveforms. The results show that higher discharge energy can be achieved when machining is done f_r even if the same capacitance is used. The relationship between discharge energy and frequency at different capacitance were investigated. It was found that f_r increases as the capacitance is decreased. In the application of high speed spindle, where the capacitance formed in the gap is 16.3pF, f_r at approximately 40MHz need to be supplied at 1μH of inductor. However, the available pulse power supply can only generate maximum frequency of 10MHz. Thus, the relationship between average discharge energy per pulse and frequency at different inductance were investigated. The results show that f_r can be reduced by increasing the inductance in the circuit.

The influence of f_r on the continuability of discharges within pulse train duration was done by identifying the number of discharges occurred continuously within pulse train durations. Sample of 300 pulse trains with number of discharges equivalent to about 20 pulse cycles were examined for pulses machined at 5 different frequencies: at resonant frequency and frequency lower and higher than that. The probability of discharges to continue within pulse train duration is highest was done at f_r with about 17 discharges. This is because at f_r, the discharge energy per pulse is higher and discharge pulse width is slightly longer compared to the other frequency. Thus, when discharge occurs, it is able to continue until the pulse power supply is stopped. When machining is done at higher or lower than the f_r, the probability to complete 20 discharges within pulse train duration reduces. Machining at f_r also results in highest MRR and largest crater size among the tested frequencies. This is because, machining at f_r can give higher discharge energy and higher probability of discharge continuity.

These proposed methods were applied in machining with non-contact electrical feeding. By fixing a cylindrical feeding electrode coaxially to the mandrel, capacitance C_1 can be formed in the gap between these two. However, by fixing the small feeding electrode to the mandrel, only small capacitance was able to be formed. Since feeding electrode is too small, sufficiently large discharge energy cannot be obtained due to small C_1. Thereby, discharge is difficult to sustain within the pulse train duration. To solve this, methods to increase the capacitance were proposed and discussed. The feeding capacitance C_1 can be calculated using the following equation:

$$C_1 = 2\pi\varepsilon \frac{L}{\ln\left(\frac{b}{a}\right)} \tag{1}$$

In this equation, ε is permittivity of the gap (air: $8.8542\text{x}10^{-12}$ F/m), a is the outer diameter of tool electrode holder, b is the inner diameter of feeding electrode and L is the length of the feeding electrode. With feeding electrode 1 when a=5mm, b=5.2mm *and* L=20mm, the C_1 is 28.4pF. If the same feeding electrode is used and the gap is filled with ethanol, the calculated capacitance is 689.7pF. The relative permittivity, ε_r for ethanol is 24.3 times higher than air. The pulse of the discharge current and discharge energy per pulse can be improved tremendously. However, ethanol is easy to evaporate and must be constantly fed to the gap of rotated mandrel using a pipette during machining and it is difficult to maintain the existence of ethanol in the gap. From the Eq. (1), if L is maintained at the same length, the change in diameter of a=19.8mm and b=20.0 increases the C_1 to 118.8pF. C_1 of this feeding electrode 3 can be increased because the surface area is enlarged. With this, the average energy per pulse is 3 times higher compared to feeding electrode 1. Capacitance can be increased further if the surface area between the inner and outer feeding electrode can be increased using labyrinth feeding electrode.

The labyrinth feeding electrode consists of two parts; inner and outer feeding electrode. The inner electrode was designed to be smaller than the outer electrode. The inner feeding electrode rotates together with the mandrel during machining while the outer part remains static. Thickness of the pair after assembly is 2.8mm. With this design, there is more area for the capacitance to form. To achieve larger capacitance, more pairs were assembled together. With L= 11.4mm; nearly half of the length of feeding electrode 3, the average discharge energy per pulse for labyrinth feeding electrode is nearly the same as feeding electrode 3. If the length is the same as feeding electrode 3, it is expected that the average discharge energy per pulse can be increased to 1.5 times larger with the labyrinth feeding electrode. Hence, higher capacitance at was able to form with larger diameter feeding electrode and the newly developed labyrinth feeding electrode.

With feeding electrode 3, investigation on the influence of tool rotation speed was performed by increasing the feed speed. Here the tool was rotated at 900rpm and 3300rpm. The maximum MRR for 900rpm is about 7323μm^3/s at 0.2μm/s feed speed. On the other hand, the maximum MRR for 3300rpm is 42077μm^3/s at 1.0μm/s. This shows that rotation speed does influence on the maximum material removal. This is because, the surface of the tool electrode can be cool during machining at higher tool rotation speed. Therefore, localized discharge and abnormal arc is less likely to occur resulting in higher MRR. In addition, at higher speed of tool electrode rotation, debris can be removed efficiently from the gap resulting in better machining accuracy. The results obtained from this study can be used to comply previous research in achieving micro EDM from roughing to finishing with non-contact electrical feeding.