Performance of Electrochemical Discharge Machining by Forced Discharge Dispersion (2nd Report) Monitoring of Machining Current

Katsushi Furutani*, Hiroyuki Shintani*, Yasuo Murase*, Shuichi Arakawa*
(Received Dec. 24, 2017)

* Toyota Technological Institute, Nagoya 468-8511, Japan

Abstract

This paper deals with the monitoring of the current during electrochemical discharge machining (ECDM) with multiple electrodes. A gravity-feed-type unit with six electrodes for ECDM was fabricated. The polarity of the electrodes was set to be negative. While some holes were machined by ECDM on glass, the discharge current was forced to disperse by switching the electrodes to decrease the number of cracks (divided power). The current in the divided power was observed during the machining process and compared with those in the cases of multiple electrodes connected electrically in parallel (equipotential) and of a single electrode. Bubbles were generated by current pulses with a duration of several milliseconds when the voltage was applied. However, they disappeared during pulse intervals. A current pulse with a duration of two to five milliseconds preceded a series of sharp pulses below 200 μ s in the single-electrode and divided power methods. Long and low-peak-current pulses frequently occurred, and the current pulses were concentrated at the electrodes at the two ends with equipotential power.

Key words: multiple electrodes, bubble, divided power, equipotential power, discharge, electrolysis.

1. INTRODUCTION

Flexible machining methods without preprocess are required for machining brittle insulated materials such as glass and piezoelectric ceramics. Electrochemical discharge machining (ECDM) is a solution of this demand because of simple and small structure of the machining units¹⁾²⁾.

Electrolyte such as sodium hydroxide solution is used for working fluid in ECDM. While a tool electrode as a negative electrode is gently pressed onto a workpiece and the applied voltage is gradually increased, a whole surface of the tool electrode is covered so that discharge is occurred between the tool electrode and electrolyte¹⁾. The discharge heat and/or Joule heat by the current flowing through the boundary of bubbles³⁾ accelerate the chemical reaction of the workpiece with the electrolyte. In ECDM with the electrolyte containing sodium ion (Na^+), the sodium ion dissolves the bond of O-Si-O and sodium silicate is generated as follows⁴⁾.

Then the sodium silicate is dissolved into the electrolyte and the workpiece surface is removed. Because the insulated materials have low thermal conductivity, thermal expansion causes cracks around machined areas.

The authors have built a lathe-type electrochemical discharge machine in trial⁵⁾. Then, a glass rod was machined while discharge points were shifted for cooling its surface. In addition, the principal force was measured during ECDM.

Consequently, it was cleared that the glass was mainly removed by dissolving the generated sodium silicate into the electrolyte rather than by subliming by the discharge heat and/or scraping with the tool electrode mechanically⁶⁾.

On the other hand, in the dot-matrix electrical discharge machining, a three-dimensional shape was machined by feeding six tool electrodes independently⁷⁾. The independent supply of the electricity caused crack-less machining⁸⁾. From this result, it was expected that the forced-discharge dispersion decreased cracks also in ECDM. Based on this idea, six holes were machined on a glass plate by ECDM. After performance by the forced-discharge dispersion (divided power) was compared with those by electrically connecting in parallel (equipotential power) and of a single electrode in the previous report⁹⁾, shape accuracy by the divided power was higher than that by the equipotential power and hardly generated cracks. Although the current during machining may considerably affect the removal process and the generation of the bubbles, the difference among the supplying methods of the current has not been cleared. In ECDM, the monitoring of the current is useful for analyzing the machining phenomena¹⁰⁾.

This paper describes the current by the forced-dispersion among the multiple electrodes in ECDM.

2. EXPERIMENTAL SETUP

Figure 1 shows a structure of the machining

Fig. 1 Machining unit⁹⁾

unit⁹⁾. Six tungsten electrodes sleeved with pin vises were radially arranged at the upper holder and aligned in line with an interval of 0.8 mm at the lower guide. The electrodes numbered from 1 to 6 leftward were insulated with fluororesin tubes with inner and outer diameters of 0.32 and 0.62 mm and exposed 4 mm in electrolyte. They were fed by the gravity and pressed onto a glass plate as a workpiece.

A pulse voltage was consecutively applied to the electrodes. Because a discharge point is cooled during the intervals with the pulse power supply, the heat-affected zone (HAZ) is reduced⁹⁾. Figure 2 illustrates three types of the discharge circuits: (a) single electrode, (b) divided power and (c) equipotential power. In the divided power, the applied voltage to the tool electrodes was switched with N-channel MOS-FETs with an on-resistance of 1 Ω by synchronizing with source pulses. Because the MOSFETs were driven with a ring counter composed of a TTL-IC through photo-couplers, they were always switched in order from Electrodes 1 to 6. In order to avoid the reverse current by the discharge between the electrodes and to measure the current, a fast recovery diode with a maximum reverse voltage of 200 V, a junction capacitance of 40 pF at 50 V and a reverse recovery time of 100 ns and a resistor of 1 Ω were inserted in series in each branch. The voltage drop at the diode and the resistor was negligible rather than the source voltage.

Table 1 shows the machining conditions⁹⁾.

Fig. 2 Discharge circuit⁹⁾

Table 1 Machining conditions⁹⁾

Gap voltage	70 [V]
Pulse duration and interval	80 [ms], 20 [ms]
Tool electrode	$\phi 0.3$ [mm] tungsten (-)
Anode	Graphite
Resistor for current measurement	1 [Ω]
Electrolyte	10[wt%] NaCl
Mass of pin vise	19 [g]
Workpiece	t1.3 [mm] Soda lime glass
Machining time	0.5 - 40 [min]

Tungsten rods with a diameter of 0.3 mm and soda lime glass plates were used for the tool electrodes and workpieces, respectively. A solution of sodium chloride was used for working fluid and was replaced within a total machining time of 60 min.

The voltage and current waveforms were recorded with a 12-bit digital oscilloscope with a sampling speed of 2 MS/s and an analog band width of 3 MHz.

3. MACHINING EXPERIMENTS

3.1 Current waveforms

Current waveforms after machining for 40 min were compared. Figure 3 shows waveforms by the single-electrode method. Each triangle in the vertical axis indicates the zero level. The voltage was applied during the high level of the clock signal in Fig. 3 (a). Figure 3 (b) shows an expanded view from 0.305 to 0.320 s in Fig. 3 (a), which is

Fig. 3 Example of machining current for single electrode

just after applying the voltage. When the voltage was applied at 0.305 s, current flowed for several milliseconds. Then spike current with a duration less than 100 μ s intermittently flowed. Current pulses with a duration of several milliseconds sometimes flowed in addition to other time during applying the voltage. These phenomena were repeated whenever the voltage was applied. In the observation with a high speed camera, bubbles grew after the generation with the first current pulse, and then a discharge occurred. The bubbles were disappeared during the intervals. Thus, the first pulse with a duration of several milliseconds generated the bubbles and the following current pulses with a shorter duration were discharge. A current of 0.3 A constantly flowed during applying voltage.

Figure 4 shows waveforms by the divided power. The gate signal was consecutively applied to the gates of MOSFETs as the switching devices from Electrodes 1 to 6. The gate signal only to Electrode 1 is shown in Fig. 4 (a). The similar current to one shown in Fig. 3 was observed at the channel applied the voltage. Because the current waveform at Electrode 1 was similar to ones at the others, bubbles generated with the other electrodes did not affect the discharge generated at Electrode 1. While the voltage was cyclically applied to the electrodes, the discharge did not occur for 500 ms and the machined areas were cooled. The expanded view shown as Fig. 4 (b) was also similar to the trend shown in Fig. 3.

Figure 5 shows waveforms by the equipotential power. Because all electrodes should be covered with enough bubbles for generating discharge, many current pulses with a long duration and small peak were observed as shown in Fig. 5 (a). The current to generate the bubbles flowed from the electrodes simultaneously. Figure 5 (b) shows these and short current pulses generated after a short intervals. Current pulses with small peaks, apparently discharge, rarely occurred from only an electrode simultaneously.

Because the shortest pulse was about 20 μ s in all supplying methods of the electricity, a sampling rate of 2 MS/s was adequate.

3.2 Number of current pulses at each electrode

A program to process data acquired with the digital oscilloscope was written in C language. In the results shown in Figs. 3 to 5, the steady-state current was about 0.3 A in each electrode, and the noise was equivalent to less than 0.2 A while the voltage was applied to one of the other electrodes. In order to avoid the disturbance by the contained noise, the different threshold currents for rising and falling were set to 0.5 and 0.3 A, respectively. In this program, current pulse was counted by classifying by the peak and pulse duration. Consequently, the pulses were not distinguished between the discharge and the pulse mainly to generate the bubbles by electrolysis in this program.

Figure 6 shows the number of pulses for 5 s after 20-min machining in each supplying method of the electricity. In the single-electrode method, the number of pulses was 3700. In the divided power, the number of pulses at each electrode was from 890 to 950. In the equipotential power, though more pulses were observed only at Electrode 6 than the others, that at Electrode 1 was also larger than those at Electrodes 2 and 3. In the equipotential power, the working fluid was electrolyzed at all electrodes simultaneously. Because Electrodes 1 and 6 were either end of the electrode line, the discharge to the electrolyte frequently occurred and the number of pulses there were increased. Because the row of the electrodes was not exactly symmetrical at the lower electrode guide, the bubbles were unevenly accumulated around the electrodes so that the discharge also occurred unevenly.

Although the number of the current pulses was seldom varied in the divided power, the number of pulses at Electrode 1 and 6 were changed in the equipotential power even in a short machining time. Thus, the performance by the equipotential power was affected by the surrounded bubbles more easily

(a) Long period

(b) Expanded view

Fig. 4 Example of machining current by divided power

(a) Long period

(b) Expanded view

Fig. 5 Example of machining current by equipotential power

than that by the divided power.

3.3 Number of current pulses at other electrodes

The current pulses at each electrode were counted from the measured data. The number of current pulses at other electrodes (hereafter OE number) is defined as the number of discharges occurring at the other electrodes after a discharge occurred at an electrode, by following Reference 8). Figure 7 illustrates how to count OE number for Electrode 1. During the period (a), after a discharge occurred at Electrode 1, discharges occurred once at

Electrode 2 and twice at Electrode 6, and then a discharge occurred at Electrode 1 again. In this case, OE number is 3. During the period (b), discharges successively occurred twice at Electrode 1. In this case, OE number is 0. During the period (c), discharges occurred twice at Electrode 1 as well as the period (b) though a discharge occurred also at Electrode 4 at the same time as the second discharge at Electrode 1. Since the simultaneous discharge is not counted, OE number is 0 also in this case. This state sometimes observed when

Fig. 6 Pulse distribution 20 min later

Fig. 7 Definition of number of current pulses at other electrodes (OE number)

current with a duration of several milliseconds flowed in the equipotential power. The state that OE number is zero means successive discharges at an electrode.

Figure 8 shows examples of OE number. The horizontal and depth axes indicate OE number and the electrode numbers, respectively. OE numbers over 10 times were omitted because they were rare. In the divided power shown in Fig. 8 (a), discharges occurred only at the electrode applied the voltage. Consequently, OE number was 0 for all the electrodes, and OE numbers were almost flat as the numbers at each electrode were also flat as shown in Fig. 6. In the equipotential power shown in Fig. 8 (b), the 0-times was notably observed at Electrodes 1 and 6. However, OE numbers over 1 were also observed and the discharges distributed in 80 ms which is a duration of a pulse.

In the previous paper⁹⁾, the average removal amount in the divided power was larger than that in the equipotential power in the machining time from 20 to 40 min. The dispersion of the removal amount was very large in the equipotential power, especially the removal amount was very large at Electrode 6. On the contrary, the dispersion was

(a) Divided power

(b) Equipotential power

Fig. 8 Number of current pulses at other electrodes

very small in the divided power. From the results shown in Figs. 6 and 8, the removal amount was large in the case that the number of the current pulses was large and OE number of 0 times was frequently observed. In addition, the small dispersion in the divided power coincided with the small dispersion of the pulse counts.

3.4 Duration and peak of current pulses

The measured current pulses were classified by duration and peak. The peak was defined as a maximum in a detected pulse, and the duration was defined as a half-value width between the peak and 0.3 A that always flowed even without discharge. The classes of the duration and peak are 20 μ s and 0.25 A, respectively.

Figure 9 shows a pulse distribution at Electrode 2 for 5 s at a machining time of 30 min. Because the threshold to detect the rise of a pulse was set to 0.5 A, no class less than 0.5 A appears. In all the supplying methods, the trends of the distribution did not change over time. In the single-electrode method shown in Fig. 9 (a), the distributions of the duration and peak were broader than the others. The

Fig. 10 Distributions of peak and duration at electrode 6 by equipotential power

Fig. 11 Progress of bubble layer and gas film formation, and discharge path

Fig. 9 Distributions of peak and duration (Electrode 2)

frequency was large in the range of a peak from 0.5 to 1.0 A and a duration less than 40 μs in particular.

In the divided power shown in Fig. 9 (b), the frequency at a peak from 0.5 to 0.75 A and a duration less than 20 μs was largest in the measured range. Although the total number of pulses was smaller than that in the single-electrode method, the ratio was the same. The pulse over 1 A frequently occurred from 100 to 200 μs . There was no difference among all the electrodes. In the equipotential power shown in Fig. 9 (c), the range of the peak and duration was the same as the others. The trend of the distribution was indistinct because of the small number of pulses. Figure 10 shows a distribution at Electrode 6 in the equipotential power. It was similar to those of the others as well as at Electrode 1. Because the bubble spread radially from the ends of the electrode row⁹⁾ and this phenomenon was the same as the others, the distribution of the current pulse was also the same.

Figure 11 illustrates a generation process of the bubbles and discharge position. In the early stage of the bubble generation shown in Fig. 11 (a), the bubbles are generated on the surface of the tool electrode by electrolysis as soon as the voltage is

Fig. 12 Discharge paths during machining

applied. Then the tool electrode is covered with the bubble as shown in Fig. 11 (b). After that, a gas film is formed with coalescent bubbles and the tool electrode is insulated from the electrolyte as shown in Fig. 11 (c)¹²⁾. Because the surface tension of the electrolyte is larger than pure water and oil, the bubbles in the electrolyte are easy to coalesce. In the case that the current is sometimes 0 A¹²⁾, discharge can occur. On the other hand, the current was always over 0.3 A in Figs. 3 to 5. Consequently, it is impossible that the tool electrode was insulated completely from the electrolyte and the discharge occurs in the film. Another model in which the current flows in the bubble boundaries as shown in Fig. 11 (b) has been proposed³⁾. Figure 12 illustrates current paths based on this model. The tip of the tool electrode touches a workpiece by the gravity and the bubble amount is small due to the small gap length around the electrode tip. In addition, the path to the electrolyte through the bubbles is long. Consequently, the peak is small. The current does not flow once the boundary is broken by the current and the duration is short. Because the side of the tool electrode covered with the bubbles is wide and the length between the tool electrode and the electrolyte is short, the resistance is small. Therefore, the peak is large and the current flows through other boundaries even if a part of the boundaries is broken.

3.5 Discussions

The effect of the measured current pulse on the machined shape is discussed.

The phenomena of the bubble generation and disappearance were common in all the supplying methods. The electrolysis by applying voltage generates the bubbles to cover the tool electrodes. With a progress of the electrolysis, the bubbles were increased and gathered around the tool electrodes. As soon as some of the bubbles coalesced into a large bubble, it broke and disappeared.

Although the bubbles were continuously generated in the single-electrode method through the visual observation, the bubble layer thickness

was changed as follows. The bubbles generated in electrolysis covered the tool electrode by applying voltage. The thin bubble layer initially had a small resistance and the current with a high peak flowed near the bubble boundaries. The bubbles did not completely disappear in 20 ms after the voltage is turned off and they always clung to the tool electrode. When the voltage was applied again in this state, more bubbles clung than without initial bubbles and a thicker layer was formed. Then the peak current was small because the resistance was increased. The small current generated smaller amount of the bubbles. By repeating this process, the current with various durations and peaks flowed as shown in Fig. 9 (a). When the bubbles disappeared, fresh electrolyte flowed into the gap and Na⁺ ion for the chemical reaction was supplied. The discharge occurred there besides and the chemical reaction to generate sodium silicate was accelerated by the discharge heat. Its dissolution helped the removal.

In the divided power, the amount of generated bubbles was smaller than that in the single-electrode method through visual observation. The interval between the pulses was longer than the others so that the bubbles disappeared in the intervals. In this case, because a thick bubble layer was rare and the resistance was small, high peak current flowed as shown in Fig. 9 (b). There were fewer bubbles around all the electrodes initially, and each electrode hardly affected its adjacent electrodes. This is why the dispersions of machined depth, and major and minor axes were small among the electrodes⁹⁾.

In the equipotential power, the amount of the generated bubbles was the most through visual observation. Because six electrodes were connected in parallel, the overall interval was the same as that in the single-electrode method. In addition, the total surface area of the immersed electrodes was large. Consequently, the bubble amount insulating the electrodes from the electrolyte was large and the resistance was the smallest. The large bubbles broke and disappeared after the large amount of the generated bubbles coalesced. Therefore, long pulses to generate the bubbles by electrolysis frequently flowed to cover all the electrodes whereas short pulses presumed as the discharge hardly occurred. From Electrodes 2 to 5, the bubbles were accumulated. The number of current pulses was small and the peak was also small. Because Electrodes 1 and 6 located at either end of the electrode row, they were soaked in the fresh electrolyte and chemical reaction was active. Therefore, the removal amount was large at Electrodes 1 and 6.

As mentioned above, in order to improve the performance in the machining of insulated materials by ECDM, it is preferable to restrict the generated area of the bubbles to the inside of the holes by the

divided power as well as to restrict the generated amount of the bubble to prevent dull hole-edge or protrusions.

4. CONCLUSIONS

In this paper, the current by the forced-dispersion among the multiple electrodes was measured in ECDM. Conclusions can be drawn as follows.

- (1) The distributions in the single-electrode method and divided power were similar to each other because the discharge occurred after the bubbles were generated around the electrodes applied the voltage both in the powers.
- (2) In the equipotential power, the discharge frequently occurred at the electrodes arranged either end of the row because the bubbles accumulated the middle of the row much so that the resistance was high.
- (3) The discharge current for removal was within a pulse duration less than 40 μ s and a peak less than 1 A.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Hiroaki Matsubara of Toyota Technological Institute for his helpful cooperation.

A part of this study was financially supported by Grant-in-Aid for Scientific Research (C) (18560118) and (21560134), by the Support Program for Forming Strategic Research Infrastructure for Private Universities, "Research Center for Smart and Tough Machines," a matching fund subsidy by Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan, and by Strategic Innovation Promotion Program (SIP) by New Energy and Industrial Technology Development Organization (NEDO).

REFERENCES

- 1)H. Kurafuji, K. Suda: Electrical Discharge Drilling of Glass I, Ann. CIRP, Vol. 16, (1968), pp. 415-419.
- 2)R. Wüthrich, V. Fascio: Machining of Non-conducting Materials Using Electrochemical Discharge Phenomenon – An Overview, Int. J. Mach. Tool. Manuf., Vol. 45, No. 9, (2005), pp. 1095-1108.
- 3)I. Basak, A. Ghosh: Mechanism of spark generation during electrochemical discharge machining: a theoretical model and experimental verification, J. Mater. Process. Technol., Vol. 62, No. 1-3, (1996), pp. 46-53.
- 4)A. Paul: Chemistry of Glasses, Chapman and Hall, London, UK, (1982), pp. 109-111.
- 5)K. Furutani, H. Maeda: Machining glass rod with lathe type electro-chemical discharge machine, J. Micromech. Microeng., Vol. 18, No. 6, 065006, (2008), pp. 1-8.
- 6)K. Furutani, K. Arai: Measurement of Machining Force in Lathe Type Electro-chemical Discharge Machine, Proc. 11th Int. Conf. euspen, Como, Italy, (2011), pp. 220-223.
- 7)K. Furutani, T. Enami, N. Mohri: Three-dimensional Shaping by Dot-matrix Electrical Discharge Machining, Precis. Eng., Vol. 21, No. 2/3, (1997), pp. 65-71.
- 8)N. Mohri, K. Furutani, K. Shirai, T. Enami: Forced Discharge Dispersion by Dot-Matrix Method, Ann. CIRP, Vol. 46, No. 1, (1997), pp. 139-142.
- 9)K. Furutani, H. Shintani, Y. Murase, S. Arakawa: Performance of Electrochemical Discharge Machining by Forced Discharge Dispersion, Int. J. Electrical Mach., No. 19 (2014), pp. 9-15.
- 10)W. Y. Peng, Y. S. Liao: Study of electrochemical discharge machining technology for slicing non-conductive brittle materials, J. Mater. Process. Technol., Vol. 149, No. 1-3, (2004), pp. 363-369.
- 11)D. J. Kim, Y. Ahn, S. H. Lee, Y. K. Kim: Voltage pulse frequency and duty ratio effects in an electrochemical discharge microdrilling process of Pyrex glass, Int. J. Mach. Tool. Manuf., Vol. 46, No. 10, (2006), pp. 1064-1067.
- 12)A. Kulkarni, R. Sharan, G.K. Lal: An experimental study of discharge mechanism in electrochemical discharge machining, Int. J. Mach. Tool. Manuf., Vol. 42, No. 10, (2002), pp. 1121-1127.