Discharge Machining of Insulating Si_3N_4 Ceramics with added Al_2O_3 -Comparison with Sinking and Wire EDM-

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Abstract

Insulating ceramic materials can be machined by electrical discharge machining (EDM) using the assisting electrode method with a sinking or wire EDM machine and electrically conductive material. In this machining process, electrically conductive carbon and carbide products adhere to the surface of the workpiece during discharge. The characteristics of the layer are affected by the electrical machining conditions and the physical characteristics of the workpiece. Typically, the machining conditions for SEDM and WEDM are very different. In this paper, to investigate the difference in the machining properties of SEDM and WEDM, several experiments were carried out by varying the amount of Al_2O_3 added to the Si_3N_4 ceramics, and the size of the tool electrode. The material removal rate and the surface roughness were estimated for workpieces following EDM. Discharge waveforms were observed with a digital oscilloscope and analyzed by using the designed program. Machining properties were analyzed by considering the structure of the workpiece and the electrode diameter.

Key words: Insulating sintering ceramics, sinking electrical discharge machining, wire electrical discharge machining

1. INTRODUCTION

More than 20 years ago, insulating ceramics became a machinable material due to the introduction of electrical discharge machining (EDM) technology. EDM of ceramics was proposed and developed by the authors' research group^{1), 2)}. Precise, three-dimensional complex shapes of insulating materials such as Si_3N_4 , SiC , ZrO_2 , AlN , glass, china, natural diamond and plastics were machined using sinking EDM (SEDM) and wire EDM (WEDM)^{3), 4), 5)}. Many experimental trials were performed to produce better machining properties. Although ceramic parts were successfully produced using the newly devised EDM methods, the following theoretical and practical problems remain unresolved for SEDM and WEDM.

(1) Because the thermodynamic, thermochemical and heat physical characteristics are different for SEDM and WEDM, there is a large variation in suitable EDM conditions. The production and adhesion mechanisms of the electrically conductive layer have not yet been clarified. Abnormal discharge waveforms are generated and their distribution varies with each workpiece.

(2) The removal method for the electrically conductive layer from each EDM processed surface has not yet been established due to the differences in adhesion strength and layer structure.

(3) The machining properties vary with the tool electrode size.

In this paper, to clarify the effects of the structural component of the workpiece and the discharge generation conditions on the machining properties, three types of ceramics materials were sintered by

varying the amount of Al_2O_3 added to $\text{Si}_3\text{N}_4\text{-Y}_2\text{O}_3\text{-Al}_2\text{O}_3$. These sintered workpieces were machined by SEDM and WEDM. Due to differences in the EDM setup conditions, the extrusion of debris from the discharge atmosphere and the tool electrode material contributed to a variety of machining properties. The size of the tool electrode area was also investigated to analyze the difference of the discharge generation condition on an uneven shape surface with consideration of the EDM wire diameter. The discharge generation conditions were estimated by the discharge waveforms.

2. THE ASSISTING ELECTRODE METHOD

As it has been previously reported, the machining process and mechanism of EDM were used with consideration of the surface modification phenomena^{1), 2)}. A schematic illustration of the assisting electrode method for SEDM is given in Fig. 1. The workpiece surface is covered with an electrically conductive material. The machining process is carried using only working oil.

As reported before, the discharge starts from the electrically conductive material. Then, the discharge occurs continuously throughout the covered material and into the insulating area. The continuous discharge indicates that electrically conductive products became adhered to the workpiece during discharge. The adhered layer maintains the electrical conductivity after the assisting electrode material is removed. However, excessive layer adhesion degrades the surface properties and has adverse effects on machining accuracy^{1), 2)}.

Figure 1 Illustration of the assisting electrode method for sinking EDM

It is assumed that the same adhesion mechanism generally occurs in SEDM and WEDM, but each method has different machined surface conditions. The electrical machining conditions must be individually modified for the physical characteristics of each workpiece and machining method. To investigate the particular discharge generation mechanism on insulating ceramics in working oil, the following EDM experiments were carried out.

3. EXPERIMENTAL METHOD

Fig. 2 illustrates the setup of SEDM. A commercial SEDM machine with a modified electrical circuit control system was used in the experiments. The electrical machining conditions were selected based on previously examined machining results for standard commercial insulating Si_3N_4 ceramics. Table 1 shows the SEDM conditions.

Fig. 3 shows the outline of the wire EDM (WEDM) method. The electrical circuit control system for the selected WEDM conditions is shown in Table 2. Si_3N_4 - Y_2O_3 - Al_2O_3 workpieces were sintered with three different amounts of added Al_2O_3 . As shown in Table 3, the amount of Y_2O_3 was constant (5 wt%) across the samples, and the amount of Al_2O_3 varied from 3 to 5 wt%. In SEDM, cylinders of pure copper with diameters from 1 to 5 mm were used as the tool electrode material.

In WEDM, a normal Cu-Zn wire of $\phi 0.2$ mm was used as the wire tool electrode. The machining properties evaluated were the material removal rate (MRR), the wear ratio of the tool electrode in SEDM (TWR), the surface roughness following EDM, and waveform analysis, which was carried out using a system designed for this experiment. The waveforms were divided into four types, based on the observed generation patterns of the discharge voltage and current. The data were recorded by a digital system waveform analysis, which was specially designed for

Table 1 SEDM conditions

Electrode polarity	Negative
Discharge duration [μs]	1
Pulse interval time [μs]	10
Setting current [A]	5.0
Open circuit voltage [V]	100
Servo voltage [V]	60

Table 2 WEDM conditions

Electrode polarity	Negative
Discharge duration [μs]	2
Pulse interval time [μs]	15
Setting current [A]	6.7
Open circuit voltage [V]	100
Servo voltage [V]	50
Wire tension [gf]	100
Wire speed [m/min]	5

Table 3 Composition of the materials

Material	Y_2O_3 [wt%]	Al_2O_3 [wt%]	Density [g/cm^3]	Bending strength [MPa]
3% (A)	5	3	3.16	890
4% (B)	5	4	3.19	790
5% (C)	5	5	3.22	790

Figure 2 Illustration of the SEDM system setup

Figure 3 Illustration of the WEDM system setup

this experiment. The waveforms were divided into four types, based on the observed generation patterns of the discharge voltage and current. The data were recorded by a digital oscilloscope. The EDM surface conditions were observed and compared by scanning electron microscopy (SEM) and laser scanning microscopy.

4. RESULTS AND DISCUSSIONS

4.1 Sinking EDM

The SEDM characteristics for the three types of Si_3N_4 were investigated. The typical displacement curve for the tool electrode is shown in Fig. 4. The curve can be divided into three parts. The first region corresponds to machining with the assisting electrode. The time period, within 1 min, is very short. In the second region (transition region), the curve maintains an almost constant value for a period of time. In the third region (stable region), the curve has a steep slope. The lengths of the first and second regions change according to the adhesion or attachment conditions of the assisting electrode material. In the transition region, the material removal phenomenon does not change with machining time. This region is assumed to exist due to the following discharge generation phenomenon: the discharge generation changes from the assisting electrode to the electrically conductive products. The length of this region varies with the generation ratio of the unstable discharge for each material. However, in the stable region, constant discharge generation occurs for a long period for each material. The relationship between the average MRR and TWR and the amount of Al_2O_3 added is shown in Fig. 5. In this figure, the removal rate is estimated within the stable region (third region). In this case, the machining properties of MRR and TWR improve with increasing Al_2O_3 content. The experiments were carried out in triplicate, and very small deviations were observed. The experiments indicate that discharge generation occurs under the stable condition. To confirm the discharge generation behavior, the surfaces of each material following EDM were observed by a laser scanning microscope. Figs. 6(a), 6(b) and 6(c) show the removed surfaces of the electrode layer for materials (3%, A), (4%, B) and (5%, C), respectively. Figure 6(d) shows the surface following SEDM with 3% Al_2O_3 , where the adhesion layer still remains. In Fig. 6(d), the thin layer covers the entire discharged surface and no microcracks are detected. This thin layer could be wiped easily with a cloth. On the removed surfaces of 6(a), 6(b) and 6(c), definite discharge marks are observed. The discharge marks are almost the same size, approximately 100 μm , on each workpiece. Fig. 7 shows the relationship between the amount of Al_2O_3 added and the surface roughness following EDM with the electrically conductive layer removed. All of the surface roughness values (R_a) are similar at about 3 μm . This

Figure 4 Typical tool electrode displacement curve for Si_3N_4 in SEDM

Figure 5 Effects of the amount of added Al_2O_3 on removal rate and electrode wear ratio

Figure 6 Observations of surface following SEDM by laser microscope

result indicates that the Al_2O_3 content does not affect the surface roughness.

The discharge waveforms were also analyzed in each experiment at intervals of 50 ms of machining time. In SEDM, the pulses of 1 ms are much longer than those in the setup period. The occupation ratios of the divided waveforms are shown in Fig. 8 for each material in the transition region and in the stable region. The waveforms are divided into four patterns: normal, long pulse, concentrated, and short circuit. Because many short circuits and concentrated pulses

are observed in the transition region, the generation ratio for the normal discharge is very small. This indicates that the electrically conductive products are produced mainly in this region. However, little difference is seen between the three sintered materials, and therefore the Al_2O_3 content does not explain the difference in the machining properties. In contrast to those in the transition condition, each material in the stable condition has many waveforms and few short circuit waveforms. However, the ratio of long pulses generated larger than that in the transition region, and the same normal waveform occupation rate is detected in the two regions.

4.2 Wire EDM

The relations between the amount of added Al_2O_3 and the MRR and surface roughness for WEDM are shown in Fig. 9. The MRR and surface roughness values decrease with increasing Al_2O_3 content. This relation shows a different trend to that for SEDM. For the large Al_2O_3 content, the surface roughness following WEDM shows a wide deviation. However, as shown in Fig. 7, the surface roughness following SEDM does not depend on the amount of Al_2O_3 added. Fig. 10 shows SEM images of the surfaces following WEDM. The adhered layer was removed by shot peening, and a hard and thick carbon layer was revealed on the surface. Small products are observed on the surface and their density decreases

Figure 7 Effects of the amount of added Al_2O_3 on surface roughness (SEDM)

Figure 8 Occupation ratios of waveforms on the stable and transition region for SEDM

with increasing Al_2O_3 content. In the 5 wt% Al_2O_3 material, some larger products are observed. In the high-temperature region during discharge, the Si_3N_4 is dissolved but the Al_2O_3 is melted. The dissolution temperature for Al_2O_3 is higher than that for the dissolved temperature of Si_3N_4 . If the adhered products were produced by the cooling process from the melt or the dissolution temperature, the product components depend on the Al_2O_3 content. However, the number of small products increases with decreasing Al_2O_3 content. This indicates that production of small products depends on the matrix elements of Si_3N_4 . On the other hand, large products are detected in the material with a higher Al_2O_3 content, so their production depends on the discharge process of the Al_2O_3 region. The adhesion strength of the layer is larger for WEDM than for SEDM. To investigate the difference in adhesion layer conditions between WEDM and SEDM, the thicknesses of the layers were evaluated by the scratch indentation method. In this method, the pressed indenter load changes continuously with the scanning direction; here, the compressed indenter shape changed at the boundary of the adhesion layer and the ceramic matrix. The layer thickness is estimated by measuring the depth at this point. The electrical resistivity of the layer was also observed with a 4-point probe electrical resistivity measurement system.

The relations between the Al_2O_3 amount and the layer thickness, the surface resistivity and the bulk electrical resistivity, which was calculated by considering the layer thickness and the surface resistivity, are shown in Fig. 11. The discharge conditions are compared with the discharge waveform patterns. In this analysis, the discharge waveforms were divided into four patterns, as for the SEDM data. Fig. 12 shows the occupation rate of waveforms for 500 ms in the stable discharge condition. The ratio of abnormal discharge waveforms increases with increasing Al_2O_3 content. It is assumed that the removal volume is correlates with the discharge power used to calculate VA, where V is the average discharge voltage, and A is the current of the normal and long pulses. The relation between the discharge power and the duration of the pulse is displayed in Fig. 13. The higher discharge power was obtained for lower amounts of Al_2O_3 (A). Lower discharge energy and a longer pulse width of 100 μs are observed for materials with higher Al_2O_3 content (materials (B) and (C)). As previously reported⁵⁾, it had been considered that the generation of long pulses assisted in the generation of the electrically conductive carbide layer on the workpiece. As shown in Fig. 11, the layer thickness increases with the increasing Al_2O_3 content. It appears that the higher Al_2O_3 content helps to produce a carbon layer on the workpiece in WEDM. This result corresponds to the behavior of long-pulse generation in the thicker electrically conductive layers of materials (B) and (C).

Figure 9 Effects of Al₂O₃ content on the removal rate and surface roughness in WEDM

Figure 10 SEM images of surfaces following WEDM

Figure 11 Effects of Al₂O₃ content on layer thickness and surface resistivity

Figure 12 Occupation ratios for divided waveforms in the stable region

4.3 Effects of the tool electrode size

To investigate the difference in the discharge behavior between WEDM and SEDM, the characteristics of the discharge process were compared. In the WEDM process, the tool electrode wire is pulled by the tensile load and is rolled up continuously, so each discharge occurs at a different place on the wire surface. As the discharge point changes every time, the heated area cools quickly. Thus, an abruptly resolidified Al₂O₃ component is produced on the machined surface. In SEDM, discharge occurs at the same tool electrode surface with dispersion condition, and abnormal discharge waveforms are easily generated. However, under the same discharge power conditions, it is assumed that the discharge crater sizes are similar, and the machining properties are controlled by the electrode size. In this research, the effects of tool electrode size were investigated in SEDM and WEDM under similar discharge conditions. In SEDM, experiments were carried out with pure copper cylindrical diameters of Ø1, 2, 3 and 5 mm. The MRR was estimated at a machined depth of 1 mm.

The correspondence of the cylindrical tool electrode diameter is next estimated. The relationship between MRR and the added Al₂O₃ amount is shown in Fig. 14 for each tool electrode size. Constant MRR values were detected regardless of the amount of added Al₂O₃ for the small diameter electrode of Ø1, 2, 3 and the wire. The MRR values for WEDM exist between Ø1 and 2. Thus, the constant value of MRR for WEDM was detected between Ø1, and 2. It was the same relation of

Figure 13 Effects of Al₂O₃ content on discharge power and pulse duration

Figure 14 Effects of the amount of Al₂O₃ content on the removal rate in SEDM and WEDM

SEDM at small size. However, when the tool diameter became larger than $\varnothing 5$, MRR increased with the increasing amount of added Al_2O_3 in SEDM. This result indicates that the machining properties affect the structure of the workpiece and the size of the removal area. We assume the following phenomena contributed to these results. The exhaustion phenomena of debris from the discharge atmosphere and the difference of the discharge generation power and the allocation ratio between the tool electrode and the workpiece were correlated on the discharged conditions. It is considered that the discharge phenomena are controlled by the occupation ratio of the carbonization process on the large tool electrode and depends on the amount of Al_2O_3 added. However, on the small electrode, including the wire electrode, the normal removal discharge process is controlled regardless of the Al_2O_3 content.

5. CONCLUSIONS

To investigate the differences between sinking and wire EDM, the effects of the amount of added Al_2O_3 on the electrical discharge machining properties for $\text{Si}_3\text{N}_4\text{-Y}_2\text{O}_3\text{-Al}_2\text{O}_3$ insulating ceramics were estimated. The effects of the tool electrode size, including the wire electrode for all materials, were investigated. The results are summarized as follows:

SEDM

(1) The machining process can be separated into three sub-processes: the assisting electrode method, the generation of carbonized products and their adherence on the workpiece, and the removal process with discharge generated under stable conditions.

WEDM

(2) The MRR and TWR improved with increasing Al_2O_3 content. However, the surface roughness was not dependent on the Al_2O_3 content.

(3) A very thin carbonized layer was produced and easily removed from the surface machined by SEDM.

(4) A thick, hard carbonized layer was produced on the surface machined by WEDM and was difficult to remove.

(5) The MRR and surface roughness became worse with increasing Al_2O_3 content.

(6) The thickness of the electrically conductive layer increased and the electrical surface resistivity decreased with increasing Al_2O_3 content.

Tool electrode size

(7) The MRR depended on only the electrode size, and remained constant regardless of the amount of added Al_2O_3 for the small electrode.

References

- 1) T. Tani, Y. Fukuzawa, N. Mohri, N. Saito, Effects of Assisting Electrode Material on the EDM Characteristics for Insulating Sialon Ceramics, *Journal of the JAPAN society of electrical machining engineers*, Vol. 30, No. 65, pp17-23, (1996).
- 2) Y. Fukuzawa, T. Tani, E. Iwane, N. Mohri, Some Machining Methods of Insulating Materials by an Electrical Discharge Machine, *Journal of the JAPAN Society of electrical machining engineers*, Vol. 29, No. 60, pp11-21, (1995)
- 3) H. Horibata, Y. Fukuzawa, N. Mohri, T. Tani, EDM characteristics of Al_2O_3 using electrode consumption, *The Japan Society for Precision Engineering*, p328, (1998).
- 4) T. Tani, Y. Fukuzawa, K. Nanbu, N. Mohri, Machining Phenomena in EDM of Insulating Ceramics with Powder Mixed Oil, *Journal of the JAPAN society of electrical machining engineers*, Vol. 36, No. 81, pp39-46, (2002).
- 5) H. Gotoh, T. Tani, Y. Fukuzawa, N. Mohri, WEDM for Insulating Si_3N_4 Ceramics, *Journal of the JAPAN society of electrical machining engineers*, Vol. 40, No. 95, pp162-168, (2006).

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