Electrical Discharge Machining by Using MAX Phase Ceramic Tool Electrodes

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(Received Dec. 31, 2019)

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Abstract
Given that copper has low hardness, the machined surface is easily peeled, and the chips are easily welded to the cutting tool. However, to obtain the tool electrode shape during machining, a specially coated cutting tool and a special milling machine are required in consideration of the machinability and the machined graphite chip. In this study, the machining characteristics of MAX phase ceramics are considered for their advantages in a new tool electrode material. Ti3SiC2 is a type of MAX phase ceramics that has excellent hardness, heat resistant, and abrasion resistant characteristics associated with ceramics. Further, it has the metallic characteristics in terms of electrical and heat conductivity. The tool electrode wear ratio and removal rate of both copper and Ti3SiC2 electrodes were compared. In this study, the effects of electrical conditions on machining and the electrode polarity on tool electrode wear ratio and removal rate were also investigated.

Key Words: Electrical discharge machining, Ti3SiC2, MAX phase ceramics, removal rate, tool electrode wear ratio

1. INTRODUCTION
The materials generally used for the tool electrodes of electric discharge machining (EDM) are copper, graphite, and copper–tungsten alloy. However, to obtain the tool electrode shape during machining, a special coated cutting tool and a special milling machine are required in consideration of the machinability and the machined graphite chip. Thus, the cost of fabricating tool electrodes for EDM is higher than that of machining parts in general. Therefore, in this study, we focused on MAX phase ceramics as a potential new material for tool electrodes. The letters M, A, and X in MAX phase ceramics represent the transition metal elements, the group elements, and carbon or nitrogen, respectively. MAX phase ceramics are chemical compounds with the ratio M_{n+1}AX_n (where n = 1, 2, 3). They have properties of both metals and ceramics, including high machinability. Hence, the complicated shape processing and precision shape processing required for the tool electrode of EDM can be easily realized by using a general-purpose cutting tool or a general-purpose machine. They also feature a high melting point and high thermal conductivity. The thermophysical properties of the tool electrodes (Ti3SiC2 and Cu) are presented in Table 1.

| Thermal properties | Ti3SiC2 | Cu |
|--------------------|--------|----|
| Thermal conductivity λ | 34 | 385 |
| W/m K | |
| Melting point θ K | > 3,273 | 1,358 |
| λθ² × 10⁸ W K m | > 3.6 | 7.1 |

International Journal of Electrical Machining, No.25, March 2020
The product of $\lambda \theta^2$ is known to have a significant effect on the discharge machining properties. As the products of $\lambda \theta^2$ for Ti$_3$SiC$_2$ and copper electrodes have the same order, Ti$_3$SiC$_2$ can be used for the tool electrodes of EDM. Therefore, MAX phase ceramics can potentially be used as tool electrode materials for EDM as they have both electric discharge machinability and machinability for achieving tool electrode shapes.

Thus, this study aims to determine the effect of machining electrical conditions on machining properties when MAX phase ceramics are used for tool electrodes in EDM to better describe their applicability.

2. COMPARISON OF MACHINING PROPERTIES WITH COPPER ELECTRODES

2.1 Experimental Method

The schematic diagram for the machining of a transistor electric discharge circuit used to perform die-milling electric discharge is shown in Fig. 1. The machining conditions are shown in Table 2. In this study, the workpiece was used carbon steel S50C, and the metalworking liquid used was a kerosene-based EDM oil. The S50C workpiece was used in this experiment because its thermophysical properties are clarified and stable electrical discharge machining is possible. A Ti$_3$SiC$_2$-sintered compact, which is a type of MAX phase ceramic, was used as the tool electrode material.

Fig. 2 shows the manufacturing process of the MAX phase tool electrode. The sintering block of the ceramic was cut into rod pieces 3 mm in diameter using the wire

| Table 2 Machining properties |
|-------------------------------|
| Workpiece       | S50C            |
| Tool electrode  | Ti$_3$SiC$_2$, Cu |
| Tool Electrode polarity | (+)            |
| Open circuit voltage | V 80           |
| Servo voltage   | V 60            |
| Discharge current | A 27           |
| Discharge duration | $\mu$s 10, 25, 50, 100 |
| Pulse interval time | $\mu$s 50       |

Fig. 1 Schematic illustration of the machining by EDM

Fig. 2 Manufacturing process of MAX phase electrode tool

EDM process and chucking on the spindle as a tool electrode. The discharge duration was varied to measure the removal rate and tool electrode wear ratio to evaluate the EDM properties. In this experiment, because the range of the set discharge duration was wide, when the duty factor was constant, the number of discharges changed significantly. Both the discharge duration and the number of discharges affected the machining properties and were considered difficult to describe. Therefore, the pulse interval time was set for stable electrical discharge machining at all discharge times. For a comparison, machining was performed under identical conditions with copper, which is used in the tool electrodes of ordinary EDM.

2.2 Experimental Results

The tool electrode wear ratio for the tool electrodes is shown in Fig. 3; the tool electrode wear ratio is extremely high for the copper electrode when the discharge duration is short, but it is low when the discharge duration is long. This is because the thermally decomposed carbon in the
machining oil becomes adhered to and protects the electrode. In contrast, the MAX phase ceramic tool electrode showed a tool electrode wear ratio of approximately 10% when the discharge duration was short, and there was no significant change even when the discharge duration was increased. The removal rate of each tool electrode is shown in Fig. 4. The removal rates were approximately the same for the EDM with copper electrodes and the EDM with MAX phase ceramics. Thus, MAX phase ceramics can be used for the tool electrodes of EDM.

3. EFFECT OF ELECTRICAL MACHINING CONDITIONS ON THE ELECTRICAL DISCHARGE MACHINING PROPERTIES

3.1 Experimental Method
To investigate whether MAX phase ceramics can be applied to the machining of difficult-to-cut materials, such as cemented carbide, the effects of electrical machining conditions on EDM characteristics were investigated. The machining conditions are shown in Table 3. The discharge current, tool electrode polarity, and discharge duration were varied to measure the removal rate and tool electrode wear ratio. Energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), and surface roughness were used to evaluate the EDM properties.

| Workpiece   | S50C          |
|-------------|---------------|
| Tool electrode | Ti3SiC2      |
| Tool electrode polarity | (+) , (−)    |
| Open circuit voltage | V 80          |
| Servo voltage | V 60          |
| Discharge current | A 27,13       |
| Discharge duration | µs 10, 25, 50, 100 |
| Pulse interval time | µs 50         |

3.2 Electrical Discharge Machining Properties
The tool electrode wear ratios under each of the machining conditions are shown in Fig. 5, where (a) depicts the situation for a positive (+) tool electrode polarity and (b) depicts the situation for a negative (−) tool electrode polarity. There was a tendency for the tool electrode wear ratio to decrease as the discharge duration became longer. This is considered to be an effect of the thermally decomposed carbon in the machining oil adhering to the electrode and acting as a protective film. However, the longer the discharge duration, the greater was the tool electrode wear ratio for the negative (−) tool electrode polarity. This is likely due to the increase in the wear of the tool electrodes as the discharging energy was increased.
The removal rates under each of the machining conditions are shown in Fig. 6, where (a) depicts the situation for a positive (+) tool electrode polarity and (b) depicts the situation for a negative (−) tool electrode polarity. There was a tendency for the removal rate to decrease with longer discharge durations for both tool electrode polarities. This is considered to be due to the decrease in the frequency of electric discharge per unit time and the increase in the proportion of concentrated electric discharges. The results described above indicate that using MAX phase ceramics in the tool electrodes for EDM shows similar machining property trends to the use of copper.

### 3.3 Observing the Surface of Tool Electrodes

The results of scanning electron microscopy (SEM) of the surface of tool electrodes after EDM for a discharge duration of 100 μs are shown in Fig. 7. Cracks were confirmed on all of the surfaces of the tool electrodes. The tool electrode wear ratio can be further reduced

![Fig. 5](image1)

![Fig. 6](image2)
if the occurrence of cracks is suppressed. Further, craters were confirmed on the surfaces of the tool electrodes. The EDM of sintered compacts prepared via electric discharge plasma sintering resulted in the removal of surfaces due to the crystal grains falling off. In the case of the electrical discharge machining being performed on a sintered body produced by the SPS method, machining may progress due to both melting removal by electrical discharge and dropping of crystal grains. However, the crystal grain dropping is not observed on the machined surface of the MAX phase ceramic tool electrode. Therefore, under this experimental condition, it is considered that the MAX phase ceramic tool electrode was worn only by melting removal by electric discharge.

### 3.4 Physical Properties of Electric Discharge

The component ratios of the Ti$_3$SiC$_2$ tool electrode surface after machining for a discharge duration of 100 µs under each of the machining conditions are shown in Fig. 8. The Ti:Si composition ratio of the Ti$_3$SiC$_2$ tool electrode was 3:1 before machining and 4:1 after machining. Furthermore, the Ti:Si ratio after EDM was approximately the same, regardless of the machining conditions. The component ratios of the surfaces of the workpieces (S50C) under each of the machining conditions are shown in Fig. 9. Ti adhesions were
confirmed on the machining surface of all the workpieces. However, as it was unknown whether the Ti had adhered as a simple substance or as a compound, XRD analysis was performed.

The results from the XRD analysis are shown in Fig. 10. As a Ti peak was confirmed on the workpieces after machining, Ti may have adhered as a simple substance. However, as the workpiece surface conditions were unknown, surface roughness was measured.

Fig. 11 shows the surface roughness of the workpiece surface by EDM for a discharge duration of 100 μs. The surface roughness of the negative electrode polarity was smaller than that of the positive electrode polarity. The surface roughness did not change significantly with the discharge current. On the negative polarity side, the current density in the arc increases, and the surface irregularities increase. Therefore, in the case of positive electrode polarity, it is considered that the Ti adhering to the machined workpiece surface was removed and the amount of adhering decreased.

4. SUMMARY

A type of MAX phase ceramic, Ti₃SiC₂, was used to analyze the effects of machining properties by EDM. In the case of the positive (+) tool electrode polarity, the tool electrode wear ratio was lower and the removal rate was faster than those for the negative (−) tool electrode polarity. The composition ratios of the MAX phase ceramic tool electrodes changed; however, the Ti:Si ratio remained approximately the same after the EDM process. It is clear that Ti adheres onto the surface of workpieces and is a simple substance for all tool electrode polarities.

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