Experimental investigations into EDM behaviors of single crystal silicon carbide

Y. Zhao\textsuperscript{a}, M. Kunieda\textsuperscript{a,}\textsuperscript{*}, K. Abe\textsuperscript{b}

\textsuperscript{a}The University of Tokyo, Hongo 7-3-1, Bunkyo, Tokyo 113-8656, Japan
\textsuperscript{b}Nippon Steel Materials Co., Ltd, 5319, Yohdo, Yorii-town, Saitama, 369-1201, Japan

* Corresponding author. Tel.: +81-3-5841-6462; fax: +81-3-5841-1952. E-mail address: kunieda@edm.t.u-tokyo.ac.jp.

Abstract

The present study aims to investigate the fundamental electrical discharge machining (EDM) characteristics of silicon carbide (SiC) single crystal material. The EDM machining performances of SiC are experimentally studied and compared to that of steel. Die-sinking EDM of SiC by utilizing copper foil electrodes was proposed and investigated. It was found that EDM characteristics of SiC have a big difference from those of steel. The EDM speed of SiC is higher and the tool wear ratio is lower compared to that of steel material, although SiC has a higher thermal conductivity and melting point. Thermal crack caused by the thermal shock of electrical discharges was found as another main factor contributing to the removal of the material in EDM of SiC material. Also it is concluded that the new foil EDM method for slicing SiC ingot has potential for slicing SiC wafers in the future.

Keywords: EDM; Single crystal SiC; SiC wafer slicing

1. Introduction

SiC (Silicon carbide) single crystals are expected to be key components for next-generation low-loss power conversion equipment in various application e.g., light emitters, high temperature and high power electronics and MEMS (micro-electro-mechanical systems) \cite{1}. This is due to its excellent properties of wide energy band gap, high breakdown voltage, high thermal conductivity, low thermal coefficient of expansion and high temperature stability. SiC wafer has a characteristic which exceeds silicon wafer for power devices supporting power electronics both on voltage resistance and on heat resistance. It can reduce the electricity loss of devices greatly to realize high efficiency and saving energy. Also the machinery based on SiC can be miniaturized because the cooling of the devices becomes needless. Therefore the research and development of SiC devices has been advancing rapidly.

As regard to the wafer production process, it’s very important to slice high quality SiC crystals into thin wafers with minimum warp, uniform thickness and low kerf loss. Otherwise it will bring great difficulty for subsequent lapping and polishing process. Meanwhile with the increasing requirements for larger size SiC wafers and cost reduction, techniques for high quality, high efficiency slicing of SiC wafers with low cost are becoming more and more important. However, since SiC is of super high hardness compared to that of Si, the conventionally used mechanical machining method, mainly multi wire saw method has some problems like bad working environment with slurry, crack generation on sliced surface, large kerf loss and most importantly, time-consuming due to low slicing speed. On the other hand, the wire electrical discharge machining (WEDM) method has shown some advantages of high speed and high surface quality in slicing of SiC wafers \cite{2}. But the mass production efficiency of WEDM is still low because it is difficult to perform multi cut at the same time. Okamoto et al developed a multi-wire EDM method to cut 3 wafers at the same time to improve the efficiency \cite{3}. In order to reduce wire vibration and perform narrower kerf width, Nishimura et al employed a track-shaped wire electrode to increase the wire tension based on the multi wire EDM system and relatively narrower kerf was obtained \cite{4}. Nevertheless wire breakage and vibration remains big problems to perform low kerf loss and high speed cutting. Therefore
in this study, the fundamental EDM behaviours of SiC are investigated and compared with those of metal materials (cool tool steel SKD11). Furthermore, the possibility of slicing SiC by utilizing foil EDM method is discussed. Table 1 shows the comparison of properties of three different materials.

Table 1. Comparison of properties of SiC, Si and Fe

<table>
<thead>
<tr>
<th></th>
<th>Electrical resistivity ($\Omega \cdot \text{cm}$)</th>
<th>Thermal conductivity $\lambda$ (W/m $\cdot$ K)</th>
<th>Melting point $\theta$ (K)</th>
<th>$\lambda\theta^2$ ($\text{m}^2\cdot\text{K}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC</td>
<td>0.013–0.025</td>
<td>490</td>
<td>3000</td>
<td>4410</td>
</tr>
<tr>
<td>Si</td>
<td>&lt;0.02</td>
<td>150</td>
<td>1678</td>
<td>422.4</td>
</tr>
<tr>
<td>Fe</td>
<td>$9.71 \times 10^{-6}$</td>
<td>80.2</td>
<td>1772</td>
<td>251.8</td>
</tr>
</tbody>
</table>

2. Experimental study of foil EDM of SiC

In this section the fundamental EDM behaviours of cutting SiC by using rectangular foil electrodes were studied. Fig.1 shows the schematic diagram of experiment setup. The experiments were conducted on a standard sinking EDM machine (Sodick C32). In the experiments, thin copper foil was used as the tool electrode and it was fixed by a precise vice which can keep the flatness of the foil electrode and servo fed to cut the workpiece. In order to reduce the vibration of the thin foil electrodes during feeding, the length of the foil electrode was limited to 5mm and a slit with depth of around 2.5mm was machined in dielectric oil. Jump motion was applied to remove the EDM debris in the gap for a stable machining process.

Fig.1 Schematic of foil EDM experiment

The workpiece was N-type SiC single crystal ingot with electric resistivity of 0.013–0.025$\Omega$·cm. The main machining conditions are shown in Table 2. The machining properties such as machining speed, tool wear and surface roughness are investigated as in the following parts.

2.1. Tool wear ratio

Fig.2 and Fig.3 shows the foil tool wear ratio variation with the change of discharge current and foil thickness respectively. The tool wear ratio (smaller than 20%) is much lower with negative foil electrode due to smaller discharge energy distribution into the cathode [5]. However when the foil electrode thickness is decreased, the tool wear ratio increases rapidly because of the smaller discharge area which would suffer a higher heat flux. Also when the discharge current increases, the tool wear ratio increases due to larger heat flux applied to the tool surface.

Table 2. Experiment conditions

| Workpiece          | Single crystal SiC
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode</td>
<td>Copper foil, width:10mm thickness: 50,80,100,200$\mu$m</td>
</tr>
<tr>
<td>Open voltage</td>
<td>120 [V]</td>
</tr>
<tr>
<td>Servo voltage</td>
<td>90 [V]</td>
</tr>
<tr>
<td>Preset discharge current</td>
<td>8, 16, 24,31.5 [A]</td>
</tr>
<tr>
<td>Discharge duration</td>
<td>3 [\mu s]</td>
</tr>
<tr>
<td>Discharge interval</td>
<td>30 [\mu s]</td>
</tr>
<tr>
<td>Dielectric fluid</td>
<td>EDM oil</td>
</tr>
</tbody>
</table>

Fig.2 Tool polarity and discharge current effect on tool wear ratio

Fig.3 Tool polarity and foil thickness effect on tool wear ratio

2.2. Material removal rate

The material volume removal rate is higher when the
workpiece is anode due to larger discharge energy distribution into the anode in every single discharge. Also it increases rapidly with increasing the discharge current. Fig.5 shows that the material removal rate increases with increasing the foil thickness but the difference is not very large. It indicates that with the same material removal volume, thinner foil electrode has a higher feed speed which can improve the area cutting speed.

Also it increases rapidly with increasing the discharge current. Fig.5 shows that the material removal rate increases with increasing the foil thickness but the difference is not very large. It indicates that with the same material removal volume, thinner foil electrode has a higher feed speed which can improve the area cutting speed.

2.3. Kerf width

Fig.6 shows the machined slit kerf width by different thicknesses of the foil electrode. The kerf width is almost independent of the polarity. The minimum kerf width is about 130µm using the thinnest foil electrode with thickness of 50µm. We can infer from the kerf width that the secondary discharge between side surface of the tool and the workpiece is very serious. Hence, insulating the tool side surface and facilitate the removal of the EDM debris in the slit is necessary to decrease the kerf loss.

Dividing the material removal rate by kerf width, we can get the cutting speed which is shown in Fig.7. The cutting speed increases with decreasing the tool thickness, which is a good advantage for EDM slicing with high speed cutting and small kerf loss.

3. Comparison of EDM characteristics between SiC and steel

To compare EDM characteristics of SiC and other materials, comparison experiments of EDM of SiC and steel (SKD11) were conducted. The differences in tool wear ratio, machining speed, machined surface roughness, et al, were investigated.

3.1. Tool wear ratio difference in die-sinking EDM

A 100µm thick copper foil with width of 10mm was used as tool electrode. All the other machining conditions are kept the same as in Table 2. Fig.8 shows the tool wear ratio difference. The plots connected by the dashed lines were under exactly the same preset machining conditions. But the measured discharge current of steel was much higher than that of SiC.
because of its lower electric resistivity. However the tool wear ratio of SiC is much lower than that of steel, which is a good advantage of using EDM to machine SiC. This reason may be that for the workpiece with higher thermal conductivity, more discharge energy can be conducted into the workpiece, and thus the discharge energy distribution into the tool electrode will be less which results in a lower tool wear ratio[6].

3.2. Wire EDM

To compare the machining characteristics of wire EDM of SiC and steel, experiments in de-ionized water by wire EDM were conducted. Taking into account the discharge frequency difference of different materials, the discharge number was accounted during machining to calculate the material removal volume per single pulse discharge. The result is shown in Fig.9. The points connected by dashed lines indicate the same preset machining conditions. Under the same setting of discharge current, the actual discharge current of SiC was much lower than that of St because of its higher electric resistance. However the material removal volume per single discharge for SiC was much higher and the value increased rapidly with increasing the discharge energy.

Fig.10 shows the machined surface roughness difference. The surface roughness of SiC was larger than that of machined steel surface although the discharge energy was smaller than that of steel. Also, as shown in Fig.11, the kerf loss of SiC was also larger than that of steel because the material removal volume per single discharge of SiC was larger than that of steel.

3.3. Reasons for high MRR of SiC

To investigate the reason for the different EDM behaviors, especially the big difference in material removal rate, the properties of SiC and iron are compared (refer to Table 1). On one hand, Yamashita et al. [7] found out by experiments that in EDM process, the value of $\lambda\theta$ is related to the material removal rate as follows:

$$\ln(MRR) \propto \frac{1}{\ln(\lambda\theta^2)}$$

Here $MRR$ refers to the Material Removal Rate; $\lambda$ is the material thermal conductivity; $\theta$ is the material melting point. The material removal rate decreases with increasing the value of the factor $\lambda\theta$. But according to Table 1, the value of SiC is almost 20 times larger than that of steel, which means that SiC should be very difficult to be machined by EDM, indicating that the value cannot explain the high machining speed of SiC.

Considering that SiC is a kind of high electric resistance material as mentioned above, which can generate Joule heat during EDM process because of the high voltage drop in the workpiece near the discharge spot, the Joule heating effect would be one of the reasons for the high machining speed [8]. Together with the heat conducted from the arc plasma, the material is
more easily to be removed, which can improve the machining speed.

On the other hand, SiC material is of high brittleness. It has been reported that the material removal mechanism of conductive ceramics is based on not only melting or vaporizing but also spalling [9]. Therefore the brittle structure may also generate cracks due to thermal-shock in EDM process which can contribute to this high removal speed of SiC material.

Based on this assumption, EDM of SiC in clean deionized water was conducted and the machined debris of them was collected and observed. The EDM debris of SiC includes not only small balls and re-solidified materials, but also many fragments with large size. Their shape is irregular and the size is ranging from several μm to around 200μm, as shown in Fig.12. These kinds of small fragments are considered to be caused by the high thermal stress in the workpiece due to the thermal shock from electric discharges. This should be another main reason for the high machining speed of SiC.

4. Conclusion

In this study, the EDM behaviors of SiC were investigated and foil electrodes were employed to slice the SiC ingot. It was found that:
1) The foil EDM of SiC is feasible and the cutting kerf loss is acceptable.
2) Negative polarity is more suitable for foil EDM of SiC with higher machining speed and lower tool wear ratio under short pulse duration.
3) The cutting speed of foil EDM of SiC can be improved by increasing the discharge current and using thinner foil electrode.
4) Under the same preset machining conditions, the tool wear ratio of EDM of SiC is much lower compared to that of steel. Also the material removal rate of EDM of SiC is much higher than that of steel.
5) Thermal cracks caused by thermal stress are considered to be one main mechanism of the removal of the material in EDM process of SiC.

In the future, longer foil tool electrode will be employed and tension force will be applied to slice SiC ingots.

References