Challenge to EDM Slicing of Single Crystal SiC with Blade Electrode Utilizing a Reciprocating Worktable

Yonghua Zhaoa, *, Masanori Kuniedaa, Kohzoh Abeb

aThe University of Tokyo, Hongo 7-3-1, Bunkyo, Tokyo 113-8656, Japan
bHamada Heavy Industries Ltd., 272-8, Takaono, Ozu-machi, Kikuchi-gun, 869-1232, Kumamoto, Japan

* Corresponding author. Tel.: +81-3-5841-6463; fax: +81-3-5841-1952. E-mail address: yonghua.zhao@edm.t.u-tokyo.ac.jp

Abstract

Single crystal silicon carbide is a promising material for producing next-generation power electronic devices owing to its outstanding physical properties of wide band gap, high dielectric strength, high heat resistance and high electron saturation drift velocity etc. However, slicing of SiC wafer is very time and cost consuming with conventional abrasive multi-wire saw method due to the extremely high hardness of SiC, especially when the diameter of SiC ingot becomes larger. In recent years wire EDM slicing method is being developed as an alternative method for wafering SiC ingots. However, wire vibration and wire breakage problems are inevitable in the process. Wire vibration causes a low cutting accuracy and wire breakage results in a low cutting efficiency. In this study, aiming to solve these problems and improve the EDM slicing performances of SiC, a new EDM wafering method which utilizes a blade electrode is proposed. The slicing process was realized by applying a relative motion between a tensioned blade tool electrode and a workpiece making use of a reciprocating worktable. The development of the experimental setup and the machining experiments are described in detail in this paper. The tool wear ratio, slicing speed, and kerf loss were investigated through slicing experiments and the characteristics of this new method are discussed.

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Keywords: EDM; electrical discharge slicing; single crystal SiC; blade tool electrode; reciprocating worktable.

1. Introduction

Single crystal silicon carbide (SiC) has superior electrical and physical properties over conventional silicon (Si) semiconductor such as wider band-gap, larger critical electric field intensity, higher thermal conductivity and higher electron saturation drift velocity etc., which enables the next generation power electronics to be much smaller, faster and more efficient. In addition, SiC-based power devices can work under extreme environments of high voltage, high temperature and high frequency. It is highly expected that the performances of a great variety of applications and systems can be improved significantly by utilizing SiC-based electronics and devices [1, 2].

However, it meets great challenges to scale out the application of SiC-based devices due to its high price. High manufacturing cost of SiC wafer is one main reason for this [3]. SiC possesses a hardness two times that of Si, causing a lengthy machining time and a large kerf loss in abrasive multi-wire saw process. In addition, due to the high hardness of SiC, diamond is the only option as the tool to slice SiC which further causes an increase of the wafer manufacturing cost. Therefore in recent years, multi-wire electrical discharge slicing (EDS), as a non-contact thermal process, is being proposed as an alternative method for slicing SiC wafer in order to reduce the manufacturing cost and improve the machining efficiency [4-10]. However, in multi-wire EDS, there is a high risk of wire breakage, which sets massive limits to the improvement of the machining rate of multi-wire EDS and the minimization of wire diameter. Furthermore, wire vibration, which exerts significant influences on the machining accuracy, cannot be avoided in multi-wire EDS [8]. Therefore, in this study, a thin blade made by foil is proposed as the tool electrode in place of wire electrode for slicing SiC wafer aiming to reduce the limitations of wire electrode and improve the wafer slicing efficiency and accuracy.
2. EDM slicing by blade electrode

EDM slicing using a thin foil blade electrode brings about many advantages over a wire electrode. As illustrated in Fig. 1, the foil blade electrode thickness can be several times smaller than the wire electrode diameter under the same tension force, which leads to a smaller slicing kerf. On the other hand, blade electrode has a low risk of tool breakage, which enables a continuous stable manufacturing process. In addition, by increasing the cross section area of the blade tool, larger discharge current and tension force can be applied, which can result in a higher machining rate and smaller vibration of electrode, respectively. In previous study, the feasibility of EDM by blade electrode has been demonstrated [11]. In this study, a blade EDM slicing apparatus was developed aiming to slice SiC ingot into thin wafers.

3. Experimental setup and reciprocating slicing method

3.1. Experimental setup

The schematic diagram of the experimental setup for EDM slicing of SiC by a blade electrode is shown in Fig. 2. A reciprocating table, of which the reciprocating speed and stroke could be adjusted, was fixed on the worktable of a standard sinking EDM machine (Sodick C32). The workpiece was fixed on the reciprocating worktable and reciprocated together with the table during machining. The blade tool electrode was evenly tensioned by a specially designed tensioning fixture and installed on the main axis of the EDM machine. The slicing was conducted by servo feeding the blade tool electrode to the workpiece along the -Z direction while the workpiece is reciprocating along the X axis direction, as illustrated in Fig. 2. The pulse power supply of the sinking EDM machine was employed to apply voltage between the tool and the workpiece to perform the machining.

On the other hand, since the worktable was reciprocating at a high speed during machining, it was difficult to perform experiments by submerging the reciprocating worktable together with the workpiece in the dielectric liquid. Therefore, in the experiments, dielectric liquid was flushed to the machining area through several nozzles by a delivery pump, as shown in Fig. 2. With the flushing method, EDM oil could not be used due to a high risk of fire. Hence deionized water was used as the working liquid. In order to ensure the resistivity of deionized water maintaining at a high and constant level, a deionized water circulating system was developed which supplies fresh deionized water to the machining area all the time during machining.

The blade tool electrode fixture used in the experiments is shown in Fig. 3. The length of the copper blade electrode was set to 150mm and the thickness of the blade was 80µm. The blade tool electrode was loaded in tension by the developed blade tensioning fixture to maintain the flatness of the blade electrode and avoid its vibration. Deionized water was flushed to the blade tool electrode by three swivel nozzles which were directly set over the blade electrode, as shown in Fig. 4.
In addition, before the experiment, the lower edge of the blade tool was dressed on-the-machine by a copper-tungsten rod electrode at the beginning to obtain an even initial gap between the blade tool and the workpiece.

Influence of the reciprocating motion on the cutting performance was investigated under the machining conditions shown in Table 1. Fig. 5 is an illustration of the machining parameters used in the experiments.

<table>
<thead>
<tr>
<th>Table 1. Machining conditions</th>
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<tr>
<td>Blade tool electrode</td>
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<tr>
<td>Workpiece</td>
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<tr>
<td>Resistivity</td>
</tr>
<tr>
<td>Reciprocating stroke</td>
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<tr>
<td>Reciprocating speed</td>
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<tr>
<td>Blade thickness</td>
</tr>
<tr>
<td>Blade width</td>
</tr>
<tr>
<td>Discharge current</td>
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<tr>
<td>Preset pulse duration</td>
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<tr>
<td>Pulse interval</td>
</tr>
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Fig. 5 Illustration of machining parameters in reciprocating slicing method

4. Experimental results and discussions

4.1. Wear of blade tool electrode

Due to the extreme small thickness of the blade tool electrode, the blade tool wear ratio is significant in machining. Fig. 6 shows an example of the tool wear after certain time of machining without reciprocating the workpiece.

![Fig. 6 Blade tool electrode wear when no reciprocating motion is applied](image)

With the reciprocating slicing method, the excessive wear of the tool electrode can be reduced as shown in Fig. 7, which shows a comparison in the tool electrode wear shape between with and without applying reciprocating motion to the workpiece. With the reciprocating motion, blade tool electrode wear could be dispersed and the tool wear length of blade was reduced considerably compared to that without applying the reciprocating motion to the workpiece.

However, unfortunately, it was found that the tool electrode wear length was not uniform. Especially at both ends of the blade electrode, which were the start and end position of a reciprocating stroke, the tool wear length was much smaller compared to that at the center part of the tool electrode. This phenomenon was caused by the shorter machining time at the start and end position of a reciprocating stroke due to a shorter dwell time of the workpiece.

![Fig. 7 Measurement results of blade tool electrode wear shape](image)

Based on the mechanism above, the tool wear shape was improved by adjusting the reciprocating speed at the start and end stage of a stroke. As shown in Fig. 8, by increasing the dwell time of the workpiece at the start and end stage of the reciprocating stroke, the tool wear length became more even compared to that without control of the reciprocating speed. However, it was difficult to make the tool wear length to be completely even within the reciprocating stroke.

![Fig. 8 Influence of the reciprocating speed on the tool wear shape](image)

During slicing, the uneven tool electrode wear would result in a rapidly changing gap distance when the workpiece was applied the reciprocating motion. This may bring about
instability of the machining process, which is discussed furthermore in detail in the following sections.

4.2. Influence of reciprocating speed

The influence of the workpiece reciprocating speed on the machining rate was investigated through experiments. Here the machining rate refers to the area cutting speed defined as the machined area of the workpiece per unit time. The reciprocating stroke of the workpiece was set as 80mm. The experimental results are shown in Fig. 9. The point marked by diamond shown in Fig. 9 indicates the tool length wear ratio of blade electrode without the reciprocating motion. In the case of reciprocating slicing method, it was expected that the machining rate could be improved by increasing the reciprocating frequency since the removal conditions of EDM debris in the discharge gap could be improved by the reciprocating motion of the workpiece. Experimental results showed that the average cutting speed increased to a certain extent when the reciprocating motion of the workpiece was applied at a low reciprocating frequency. With increasing the reciprocating frequency furthermore, however, the cutting speed decreased instead. At a certain point, the blade tool electrode was deformed and the machining could not proceed anymore due to collision between the blade tool electrode and the workpiece. The reason for the collision was considered as the following.

In the slicing process, the servo feed direction of the blade tool electrode, as illustrated in Fig. 2, was perpendicular to the reciprocating direction of the SiC workpiece. Due to the uneven tool wear length of the blade tool electrode along the workpiece reciprocating direction, the change of gap distance was very rapid during the machining. Therefore, the respond speed of the servo feed system must be high enough to detect the rapidly changing gap conditions to achieve a stable machining process. Too frequent change of the gap distance, on one hand, would aggravate the load of the servo feed control system, which always tends to achieve a constant gap distance, and result in a lower machining rate. On the other hand, if the reciprocating frequency was increased too much, the gap change speed would exceed the capacity of the servo feed control system and eventually the servo feed could not work normally, which was considered to be the reason why collision occurred between the blade tool electrode and the workpiece causing the deformation of the tool when the reciprocating frequency was set too high.

4.3. Cut kerf width

Fig. 10 shows the obtained cut kerf width under different reciprocating frequency. It is found that with increasing the reciprocating frequency, the kerf width did not decrease but increased even though the flushing conditions were better with higher reciprocating frequency. It was therefore considered that the deterioration of the kerf width was probably caused by the deformation of the blade tool electrode resulted from the collision between the tool and the workpiece during machining.

Fig. 10 Machined kerf width by reciprocating EDM slicing method

4.4. Machining stability

In order to find out the most optimal machining conditions to achieve a stable slicing process, two different machining modes, as described in Table 2, were investigated and compared through machining experiments. During machining, the discharge waveforms with different machining modes were measured by an oscilloscope to evaluate the machining stability.

Table 2. Machining modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>With no jump motion of blade tool electrode</th>
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<tr>
<td>Mode 2</td>
<td>Applying jump motion to blade tool electrode</td>
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In machining mode 1, considering that the EDM debris in the machined slit could be removed taking advantage of the reciprocating motion of the workpiece, jump motion was not applied during machining in order to obtain a continuous slicing process without any interruption. It was found, however, that the actual machining could not proceed stably because of frequent short circuiting, which was probably due to collisions between the reciprocating workpiece and the tool electrode and/or accumulation of EDM debris in the discharge gap during machining. Fig. 11(a) shows the discharge waveforms measured during machining. The time when the gap voltage (voltage drop in the gap between the blade tool electrode and the workpiece) became zero indicated that short circuiting occurred during machining. In Fig. 11(a), periodic short
circuiting can be observed clearly, which was probably due to the deformation of the blade tool electrode resulted from collisions.

In order to improve the machining stability, machining mode 2 was tried out. In mode 2, jump motion (with the same direction as the servo direction) with high frequency but small height, as illustrated in Fig. 12, was applied to the tool electrode during machining. The jump up and down time was set 0.01s and 0.2s respectively. Jump speed was 16.7mm/s (jump height \( \approx \) 167µm). From the discharge waveform shown in Fig. 11(b), it can be found that no clear short circuiting existed in the machining experiment, which indicates that the stability of machining was improved. The collision problem between the tool and the workpiece could be alleviated by applying the jump motion because the gap condition could be detected by the machine every time when the jump motion returned back to the initial machining position (original servo place).

5. Conclusions

Blade tool electrode was proposed in place of wire electrode for EDM reciprocating slicing of SiC in this paper. Based on the proposed blade tool electrode, a new EDM slicing method which utilizes a reciprocating worktable was developed. The machining properties of the proposed reciprocating slicing method were characterized and the feasibility was discussed. The main conclusions were as the following:

1) The development of the experimental setup for EDM reciprocating slicing of SiC using a blade tool electrode was accomplished and the slicing experiments were successfully performed on a commercial sinking EDM machine.

2) In EDM slicing of SiC with a blade tool electrode, the tool wear in length could be decreased considerably by applying a reciprocating motion to the tool electrode compared to that without any relative motion between the tool and the workpiece. However, the tool wear length was not uniform in the reciprocating direction. By controlling the workpiece reciprocating speed, the tool wear shape could be improved, although it was difficult to make the tool wear length completely uniform.

3) By applying the reciprocating motion to the workpiece at a low reciprocating frequency, the average slicing speed of SiC could be increased to some extent due to the enhancement of removal of EDM debris in the discharge gap. A further increase of the reciprocating frequency, however, would bring about instability of machining and result in a decrease of the cutting speed due to frequent short circuiting between tool and workpiece. The reason was due to the uneven tool wear length during slicing along the reciprocating direction.

4) By applying jump motion to the tool electrode during slicing, the machining stability can be improved, although the machining rate decreased.

Acknowledgements

The authors would like to acknowledge that a part of this work was achieved under the collaborative research with Nippon Steel & Sumitomo Metal Corporation, Nippon Steel & Sumikin Materials Co., Ltd and Sodick Co., Ltd.

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