Approaches for improvement of EDM cutting performance of SiC with foil electrode

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ABSTRACT
Electrical discharge machining by foil electrode serves as an alternative method for SiC slicing. This technology uses a highly tensioned thin foil as the tool electrode. The main advantages over wire EDM are that the foil thickness can be made smaller than the wire diameter, vibrations can be avoided by applying high tension, and higher current can be supplied since there is less risk of tool breakage. However, due to the large side surface area of the foil electrode, there is a high occurrence probability of side surface discharges and high concentration of debris, which affects kerf width accuracy and machining stability. In the aim to overcome both problems, this study proposes two foil electrode designs: a foil electrode in which holes are machined and the insulation of the side surface areas by a resin coating layer of 5 μm thickness. The influences of both foil electrodes were tested with three different slicing strategies: no strategy, applying jump motion of the tool electrode, and applying reciprocating motion. From machining experiments and comparative studies of the discharge delay time, it was found that with both foil tools, the occurrence probability of side surface discharges can be reduced. In addition, the chip pocketing effect of the holes enhance the flushing conditions, resulting in a higher cutting speed.

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1. Introduction
Recent developments highlight the need to enhance the electrical and physical properties of power devices. Conventional semiconductors such as Si and GaAs, are reaching their limits in terms of maximum operating temperature, power handling and conversion efficiency in power modules. Therefore, single crystal silicon carbide (SiC) is becoming a promising material. SiC has superior properties over Si in terms of wider bandgap energy, higher electron saturation drift velocity, and higher thermal conductivity etc. Hence, SiC-based electronic devices can work under extreme environments such as high temperature, high voltage, and high frequency, in which conventional semiconductors cannot function. For this reason, SiC has become one of the most suitable materials for next generation power electronic devices. It can realize improvement of efficiency in several application fields, such as electric power distribution and aerospace applications [1–3].

Whilst SiC-based devices can realize great improvements, SiC device fabrication technologies are still not sufficiently developed to the degree required for widespread technologies. One of the main obstacles is the high price of SiC wafer and its manufacturing cost. It is therefore very important to reduce maximum material loss during the manufacturing process in order to decrease wafer costs. Moreover, SiC is considered an extremely difficult-to-machine material, due to its high hardness and brittleness, which causes great problems in machining. Hence, challenges are faced in terms of SiC slicing due to the need to reduce kerf loss and slicing time [4].

One available alternative method for SiC wafer slicing is wire electrical discharge slicing (EDS). However, with this technology, there is a high risk of wire breakage due to discharge concentration. This drawback sets limits to the improvement of machining performance and to the decrease of wire diameter. Furthermore, the tension force that can be applied to the wire is limited and wire vibration occurs, both significantly affecting machining accuracy [5,6]. In order to reduce wire vibration by applying a larger tension to the wire, Okamoto et al. [7] proposed a track-shaped section electrode. Nevertheless, the wire vibration problem cannot be eliminated.

As a consequence, in order to improve the machining performance and decrease the kerf loss, Zhao et al. [8,9] developed an EDS with a thin foil electrode. With this technique, a thin rectangular foil is used instead of wire. The foil is tensioned with a specially designed tensioner and is placed in the main axis of the sinking
EDM machine with a jig. Machining is conducted by servo feeding the foil electrode to the workpiece with the way of sinking EDM.

One of the advantages over wire EDM is that the thickness of the foil can be made smaller than the wire diameter. Furthermore, as high tension can be applied to the foil electrode, tool vibrations can be avoided. These two factors have a high impact in the value of kerf loss. Moreover, this technique has a lower risk of tool breakage problems, which is an advantage in the machining process.

2. Problems in EDM cutting of SiC by foil electrode

One of the main drawbacks of this technology is the large surface area of the foil electrode, which has a high impact on the machining performance and kerf loss. This sets limits to the improvement of SiC slicing by foil electrode.

Zhao et al. [8] demonstrated that by using a thin foil electrode, the kerf width value can be reduced from 200 μm, which is a typical value for WEDM, to 100 μm. Moreover, analysis of the cross-section profiles of cut kerf indicates that the inlet kerf width value is larger than that of the outlet and that a larger cutting depth results in a widened kerf loss. Fig. 1 shows an example of the cross-section of a cut kerf obtained using a foil electrode of 15 mm in width with a preset cut depth of 19 mm. This can be attributed to the increase of the occurrence probability of side surface discharges due to the large surface area of the foil electrode and the concentration of debris particles in the narrow side gap.

3. Proposal of new tool electrode

The present work set out to improve kerf width accuracy and machining performance in SiC slicing by foil electrode. With this aim, two foil electrode designs have been proposed.

The first alternative considers the reduction of the tool electrode side surface area by machining holes in the electrode foil, as illustrated in Fig. 2. This method has two advantages, reduction of the side surface area and improvement of flushing conditions in the side gap due to the chip pocketing effect of the holes. Both effects contribute to the reduction of side surface discharges, resulting in decreased kerf loss.

The second alternative method uses a foil electrode in which the tool side surface has been insulated by a resin coating layer. The objective is to avoid the side surface discharges and reduce the kerf loss. This theory is based on the work presented by Okada et al. [10]. They reduced the kerf width by decreasing the side surface discharges by forming a high-resistance layer on the wire surface.

The effectiveness of both foil electrodes: electrode with holes and electrode with an insulation layer, was verified through a series of machining experiments as well as with a fundamental study of the distribution of the discharge delay time.

4. Experimental method and setup

Experiments were carried out on a Sodick C32 conventional sinking EDM machine. Fig. 3 shows the image of the experimental setup. The slicing was conducted by feeding the foil electrode downward to the SiC workpiece in the Z direction. Fig. 4 illustrates the scheme of the fixture for controlling the tension force applied to the foil electrode. In the experiments, sufficient tension force was applied to the foil electrode by the compression spring to make the parallelism error within 10 μm.

As has been mentioned in the introduction, since high tension can be applied to the foil electrode, tool vibrations can be reduced. The maximum applicable tension force to the tool electrode can be calculated by the following equation:

\[ T = \sigma \cdot S \]  

(1)

Where T indicates the maximum applicable tension force, \( \sigma \) the ultimate tensile stress of the electrode material and S the cross-section area of the electrode.
Fig. 5 shows a simplified analysis model of the vibration of the tool electrode (wire or foil). Assuming that the force resulted from discharges \( F_0 \) is applied to the tool, when the tool electrode tension is as large as the maximum applicable tension force of the tool, the electrode deformation \( \delta_0 \) due to the discharge force \( F_0 \) can be calculated by the following equation:

\[
\delta_0 = \frac{1}{2} \cdot F_0 \cdot \frac{1}{T^2}
\]

As can be seen, the electrode vibration during machining is decided by the cross-section area \( S \) of the electrode.

The influence of reducing the tool electrode side surface area with holes of a diameter of 2 mm was studied. The holes were machined by sinking EDM using a copper electrode as shown in Fig. 6. The tensioned foil was placed in the worktable of the machine tool and holes were machined one by one. Considering the tool wear length at the bottom region of the foil tool electrode during the slicing, the holes were machined in the upper part of the foil electrode. The distribution of the holes on the foil is shown in Fig. 7. In order to avoid the foil breakage from the edge of the holes, the hole pitch was set as 3 mm. In addition, test machining experiments were carried out comparing the effect of the holes of 1 mm and 2 mm in diameter, in both cases the same area reduction was considered. Results show that 2 mm was better in terms of machining rate. Moreover, the foil electrode with holes of 1 mm was broken from one of the edges of the holes before finishing the slicing due to the small pitch between holes. Therefore holes of 2 mm in diameter were used in this study.

With machining holes on the foil tool electrode, the maximum applicable tension force is reduced to some extent due to the reduced cross section area. Nevertheless, the cross-section area of the foil electrode is still larger than that of \( \Phi 50 \mu m \) wire electrode even if the holes are made on the foil. Therefore, as has been illustrated by Fig. 5 and Eq. (2), compared to wire electrode, larger tension force can be applied and less foil vibration can be obtained.

Moreover, the influence of insulating the side surface of the foil by an insulation film of 5 \( \mu m \), 10 \( \mu m \) and 22 \( \mu m \) layer was investigated. The material of the insulation film was silicone modified epoxy resin (HIRESIN 018, TAKAMATSU OIL & FAT Co., LTD.) and the resin was pasted on the foil electrode by a wire bar coater. To solidify the resin film, firstly the film was applied on one side of the electrode and heated for 1 min at 100 °C by an oven (DF410, YAMATO Scientific Co., Ltd) and then the film was applied to the other side and heated for 5 min at 100 °C, followed by room temperature cooling.

Fig. 7 illustrates different types of foil tool electrodes used in the experiments. The machining conditions were determined based on previous research works [8,9]. Table 1 shows the machining and experimental conditions.

Moreover, the influences of both foil electrode designs were tested with three different slicing strategies: no strategy, applying
jump motion to the tool electrode, and application of reciprocating motion to the tool along X direction. The machining conditions of jump and reciprocating strategy are shown in Table 2.

As explained the foil electrode was loaded with tension to avoid the foil electrode vibration. After tensioning the foil electrode, parallelism error between the foil surface and the feeding trajectory was measured utilizing a CCD laser displacement sensor (Keyence, LK-G10). When reciprocating motion strategy was used, the parallelism error between the foil surface and the trajectory of the feeding axis was smaller than 15 μm. For the other two slicing strategies, the parallelism error between the foil plane and the trajectory of the feeding axis in the cutting direction was smaller than 7 μm.

5. Experimental results and discussion

To investigate the effects of the holes and side surface insulation, three factors were studied: kerf loss, cutting speed and foil electrode wear ratio.

With regard to the kerf loss, the kerf width at the inlet was larger than that at the bottom of the cut kerf and the difference between these values varied from 3 μm to 11 μm in the experiments. However, from the point of view of the final slicing result, the kerf loss at the inlet is the most important parameter to evaluate the machining performance. Therefore, in the present work the kerf loss represents the inlet kerf width and it was measured by an optical microscope. The cutting speed refers to the cut surface area of the workpiece per unit time. The electrode wear ratio refers to the ratio of the lost tool area to the cut depth area of the workpiece, which indicates that for the case of jump and no strategy, the values are comparable to the ratio of the lost tool length to the depth of cut.

5.1. Effect of making holes on foil electrode

This section presents a comparative analysis of kerf loss, cutting speed, and tool wear results between foil electrodes with and without holes.

5.1.1. Kerf loss

Fig. 8 a) shows the kerf loss obtained under different conditions. It was found that using electrodes with holes, in the case of reciprocating motion, the kerf loss was reduced. However, in the cases of jump and no strategy motion, the kerf loss did not vary significantly.

A further study concerning the influence of holes was carried out as described in Section 6. The effects of holes on the discharge delay time were analyzed for a better understanding of the possibility of reducing side surface discharges.

The lowest values of kerf loss were achieved when jump motion was applied, suggesting that improving flushing conditions in the gap, and hence decreasing debris concentration, has a significant impact on decreasing the occurrence probability of side surface discharges [11].

5.1.2. Cutting speed

Fig. 8 b) shows that cutting speed was improved with a foil electrode with holes when no strategy or reciprocating motion was used. The increase of the cutting speed is related with the improvement of machining stability, due to the chip pocketing effect of holes in the improvement of debris removal.

Comparing the results between with and without holes, significant improvement of 47% by reciprocating motion was found. This may be because the debris stuck and accumulated in the holes is easier to remove when the foil is moving in the X axis direction. In the case of no strategy, the increase was 23%. On the other hand, the jump motion shows the highest cutting speed with or without holes. However, the cutting speed did not improve with the holes when the jump motion was used.

5.1.3. Tool wear ratio

As shown in Fig. 8 c), holes were effective in terms of the electrode tool wear ratio. This effect was attributed to the higher cooling efficiency resulting from the higher convection heat transfer on the foil electrode surface due to the enhanced circulation of the dielectric liquid, which resulted in a lower thermal load on the edge of the thin foil electrode [14]. Fig. 9 shows an image of the foil tool wear after machining in the case of reciprocating motion.
5.2. Effect of side surface insulation

This section presents a comparative analysis of kerf loss, cutting speed and tool wear between a foil electrode without insulation layer, defined as no coating, and a foil electrode with side surface insulation, defined as coated.

As a preliminary step, foil electrodes without holes coated with a resin coating layer of 5 µm, 10 µm and 22 µm in thickness were studied using the reciprocating motion. Fig. 10 shows that for the case of 10 µm and 22 µm, the machined kerfs were curved, indicating that the foil electrode was deformed during machining due to collision between the tool and workpiece.

The reason is considered as the following. When the side-surface of the foil tool electrode is completely insulated, debris particles accumulated in the side gap cannot be removed because discharge does not occur in the side gap, while with using no-coated tools, debris particles in the side gap can be flushed away by the explosive force due to discharge ignited in the side gap. These results demonstrate that the resin insulation layer thickness must not exceed the discharge gap width value to realize stable machining. Furthermore, the thickness should be thin enough to maintain a certain level of electric conductivity through the resin coating layer. Consequently, an electrode foil with an insulation layer of 5 µm was used in the experiments described below. Here, it should be noted that the surface was not insulated completely with the coated thickness of 5 µm, which was verified using a circuit tester, suggesting that discharge can occur even on the side surface through the resin coating layer.

5.2.1. Kerf loss

It is found that the kerf loss decreases when coated foil electrode is used, demonstrating that the occurrence probability of discharges can be reduced by coating the side surface with a resin of 5 µm in thickness. The effect is more significant in the case of reciprocating motion. A further study was carried out as described in Section 6 in which the effect of coating was analyzed by the distribution of the discharge delay time, which is a measure to quantify the dielectric breakdown strength of the gap.

5.2.2. Cutting speed

With regard to cutting speed, Fig. 11b) shows that the cutting speed decreased when the coated electrode was used. This indicates that machining stability was affected by the insulation layer.

A possible explanation is that the reduced gap width resulted in the elevation of temperature due to restricted fluid flow and accumulation of debris particles, leading to unstable discharges [12].

5.2.3. Tool wear ratio

When reciprocating motion of the tool electrode was applied, electrode wear ratio decreased in the case of the coated foil electrode. However, in the case of no strategy and jump motion, electrode wear slightly increased probably because the tool temperature increased.

6. Discussion: influence of discharge delay time

From the machining experiments described in Section 5, it was concluded that holes and surface insulation are useful for reducing kerf loss. The results were considered due to the decrease of the occurrence probability of side surface discharges. In order to clarify this, the influence of the foil electrode design on the occurrence probability of the discharge was investigated by the analysis of the distribution of discharge delay time.

The discharge delay time, $t_d$, is defined as the interval between the application of the voltage pulse and dielectric breakdown, and it reflects the dielectric breakdown strength of the gap. Its value is difficult to establish, since the discharge delay time is determined.
by various factors, such as debris concentration, discharge area, surface profile and gap width. The discharge delay time cannot be defined in a deterministic way, but in a probabilistic way. Bommel et al. [13] verified that due to the great dispersion of results, an exponential distribution model can be used for the analysis. For this reason, different authors have made use of the Laue Plot as a comparison tool for studying different factors related to the discharge delay time. Araie et al. [15] investigated the effect of the surface roughness of a wire electrode on the discharge delay time by Laue plot. Morimoto et al. [11] found that the discharge delay time was longer with a wider gap width, less debris concentration and smaller machining area.

The Laue plot shows the percentage, \( n/N \), of electric insulation that does not break down until time \( t \) after the supply of pulse voltage. It is expressed by [11]:

\[
\frac{n}{N} = \exp \left( -\frac{t}{t_{d,\text{ave}}} \right) \tag{3}
\]

Here, \( N \) represents the number of measurements carried out for drawing the Laue plot and \( t_{d,\text{ave}} \) is the average of the measured \( t_d \):

\[
t_{d,\text{ave}} = \frac{\sum t_d}{N} \tag{4}
\]

### 6.1. Experimental setup and method

The distribution of the discharge delay time was obtained using the Laue plot. The experiments were carried out and analyzed according to the procedure used by Morimoto and Kunieda [11,16].

During the experiments, a copper electrode and a cold tool steel (SKD11) workpiece were arranged as shown in Fig. 12. A single discharge was generated between the Cu and SKD11 by a bipolar power source and a function generator, and the value of the discharge delay time was measured by an oscilloscope. To eliminate the influence of the deviation of gap width on the discharge delay time, the discharge surfaces of Cu and SKD11 were ground to achieve an accurate discharge gap width. The machining conditions during the tests are shown in Table 3. After each discharge, the steel and copper blocks were moved in order to generate the following discharge on a clean and smooth surface. This process was repeated until 20 data were obtained per electrode type. The reason why SiC was not used in the experiments is because it has difficulty in grinding the SiC surface to a small flatness error due to its significantly high hardness. However, since the purpose of this study is to conduct a relative investigation on the influence of the electrode design on the discharge delay time in EDM, it does not matter what workpiece material is used. The relative trend will be the same even different workpiece is used.

Fig. 13 illustrates the electrode blocks compared in the present study. In the case of c), holes are machined on the copper block by sinking EDM using rod electrodes. For the three cases studied, the gap width of 10 \( \mu \)m represents the distance between SKD11 surface and copper top surface under the coating film.

### 6.2. Results and discussion

Fig. 14 shows the Laue plot obtained for each electrode, and Fig. 15 shows the average discharge delay time, \( t_{d,\text{ave}} \). Results represent the trend of the distribution of the discharge delay time in order to analyze the influence of electrode design on the occurrence of probability of side surface discharges.
Results show that for both electrode with holes and coated electrode, the discharge delay time increases. Moreover, although the discharge delay time was significantly longer in the case of coated electrode, discharges occurred. This means that with a 5 μm epoxy layer, perfect insulation cannot be achieved. Hence, even though the probability of discharge occurrence is significantly low on the side surface, the debris particles can be removed by discharge which is ignited through the resin coating layer.

It can therefore be concluded that the two proposed electrodes, under the same conditions, are effective for reducing side surface discharges.

7. Strategy for optimal machining

From the results above, it can be concluded that both proposed electrodes are effective for improving the machining performance of SiC. The resin coating on the foil electrode is effective for reducing kerf loss. However, the thickness of the resin coating layer should be thinner than the gap width. Furthermore, the thickness should be thin enough to enable certain level of side surface discharge. Otherwise, the debris particles in the side gap cannot be removed, resulting in the deformation of the foil electrode. In addition, combined with jump motion of the tool electrode, optimal machining results can be achieved.

Although this work is focused on SiC slicing, the research results can be applied to general slot machining of other materials by EDM.

8. Conclusions

In the present work, attempts were made to improve SiC slicing by foil electrode. The main goal was improving kerf width accuracy by considering the influence of the occurrence probability of side surface discharge on the kerf width and machining performance. Two foil electrodes were proposed: an electrode with holes and an electrode with an insulation layer on the side surface. The effectiveness of both foil electrodes was confirmed by a series of cutting experiments and by a study on the distribution of the discharge delay time by the Laue plot. It was concluded that:

1. Using a foil electrode with holes, cutting speed increased and tool wear decreased. As a reason, the chip pocketing effect of holes improved flushing and cooling conditions, thereby the machining stability improved and the thermal load on the foil electrode decreased.
2. Kerf loss was reduced when the side surface of the foil electrode was coated with a resin coating layer of 5 μm in thickness. Thicker layers of 10 μm and 22 μm resulted in curved kerfs due to collision between the tool and workpiece.
3. The fact that the electric insulation of the resin coating layer of 5 μm in thickness was not perfect indicates that the foil electrode surface should not be fully insulated.
4. The lowest kerf loss and highest MRR were obtained when jump motion of the tool electrode was used. This indicates that debris concentration in the gap width has significant influence on the machining performance.
5. From the analysis of the distribution of the discharge delay time by the Laue Plot, it was concluded that making holes and coating the electrode surface with a 5 μm resin coating layer result in a longer discharge delay time. Hence, it was verified that both techniques can decrease the kerf width.

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