論文の内容の要旨

論文題目:

Development of Electrical Discharge Machining System for Cutting Single Crystal SiC

（単結晶 **SiC** の放電加工システムの開発）

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The thesis describes the development of new electrical discharge machining (EDM) methods and systems for application of EDM on slicing and coring of single crystal silicon carbide (SiC) ingot.

Single crystal silicon carbide (SiC), emerging as a high-performance semiconductor material for next-generation high temperature, high frequency and high energy efficiency power devices, brings new challenges to the conventional wafer manufacturing process due to its higher hardness which is almost 2 times of that of conventional semiconductor silicon. Since the hardness of SiC is approaching to that of diamond, diamond is the only tool material that is qualified for the fabrication of SiC wafer (including grinding, slicing, polishing, lapping etc.), which results in a high cost of the manufacturing process. In addition, due to its high hardness, the machining efficiency is very low when the conventionally used manufacturing process for Si is applied to SiC. On the other hand, it is possible to machine SiC by electrical discharge machining (EDM) owing to its conductivity. Besides, it was reported that wire EDM slicing of SiC wafer showed a higher machining rate and lower wafer surface damage compared to multi-wire saw method. However, the material removal mechanism and EDM characteristics of SiC are still not clear. On top of this, wire EDM, especially the currently being developed multi-wire EDM, meets several problems when it is applied to slice SiC wafer, including wire breakage, wire vibration and low productivity etc. Therefore, this thesis is devoted to clarifying the EDM mechanism and characteristics of SiC and developing new electrical discharge machining methods and systems to enhance and advance the application of EDM for cutting SiC and SiC-like materials in the future.

In Chapter 1, at first the subjects and objectives of manufacturing SiC wafer were briefly introduced and the current problems and disadvantages of the conventional standard slicing process of SiC wafer such as high cost, low efficiency, large kerf loss, and the sliced SiC wafer accuracy etc. were described. On top of these, state of the art of EDM of SiC and the development of multi-wire electrical discharge slicing (EDS) of SiC were described and the problems and difficulties of application of wire EDM for cutting SiC were described. Following this, the purpose of this research and the constitution of the thesis were described.

In Chapter 2, the differences between EDM of SiC and widely-used steel material were investigated. Experimental results showed that although SiC had a higher resistivity as semiconductor compared to steel, the material removal efficiency was much higher than that of steel. The fracture behavior of SiC by thermal shock owing to its brittleness in EDM was considered as one of the material removal mechanisms of EDM of SiC. Moreover, the influence of the high resistivity of SiC on EDM properties were revealed by conducting heat conduction analysis of single discharge using finite difference method taking into consideration the Joule heating effect in EDM of SiC. The analysis showed that Joule heating effect had a significant influence on the surface temperature at the discharge spot. However, due to the high thermal conductivity of SiC, the surface temperature dropped quickly after the discharge ignition. In addition, the influence of the crystal anisotropy on the wire EDM cutting performance were investigated. It was found that wire EDM of SiC presented a higher machining rate when the cutting direction is parallel to the *c* axis. At last, the wire EDM cutting performances of SiC were evaluated in terms of area cutting speed, surface roughness and topography, sub-surface damaged layer and wire breakage. Wire breakage problem was found serious in wire EDM of SiC especially when large duty factor was used. In order to solve the wire breakage problem, foil electrode was proposed in Chapter 3.

Chapter 3 describes the machining performance of SiC by utilizing band-shaped foil tool electrode. In order to solve the wire breakage problem and reduce the wire vibration in wire EDM slicing, foil EDM of SiC was proposed for slicing SiC instead of wire electrode because foil tool electrode could be as thin as several tens micrometers while taking a larger tension force and discharge current compared to those of wire electrode. A foil tool electrode fixture was newly developed and installed on the main axis of sinking EDM machine to perform foil EDM cutting experiments like normal sinking EDM process. The feasibility of EDS of SiC by foil tool electrode was proved by experiments. Furthermore, the influences of foil tool electrode thickness, foil tool polarity, foil tool material, cut depth, pulse conditions and dielectric liquid on the foil EDM cutting performances were described. It was found that negative tool polarity and short pulse duration were more suitable for machining SiC. Thinner foil tool electrode could achieve a higher area cutting speed, however the tool wear also increased. Copper foil was found most practical for being used as the tool electrode. EDM of SiC in water could achieve a higher machining rate, however, EDM of SiC in oil presented a better surface integrity and thinner sub-surface damaged layer. The reasons for the differences between EDM of SiC in oil and in deionized water, for example, cooling effect and permittivity of the working fluid etc. were discussed. In addition, it was found that with increasing the cut depth the foil EDM cutting speed decreased probably due to deteriorated gap conditions. The foil tool electrode wear length also increased considerably, which made it impracticable to slice large diameter ingot continuously and stably. In order to improve the flushing conditions and disperse the tool length wear, reciprocating slicing of SiC by tensioned foil electrode was proposed. In the developed method, foil EDS was conducted by servo feeding the tensioned foil electrode to the workpiece which was reciprocated by a reciprocating worktable. The development of the experimental setup of reciprocating slicing method was presented and the machining experiments of foil EDS of SiC were described. Experimental results showed that reciprocating foil EDS method could disperse the tool wear along the reciprocating direction and improve the flushing conditions. The tool wear length along the reciprocating direction in the reciprocating stroke, however, was not uniform which brought about instability of the reciprocating slicing process due to frequent change of the discharge gap width.

In Chapter 4, development of stable and continuous EDS of SiC by winding foil tool electrode method is described. In order to eliminate the instability of EDS of SiC caused by the uneven tool wear in the reciprocating slicing method mentioned above, winding foil EDS method was developed. The winding foil EDS was conducted by feeding the workpiece towards a foil tool electrode which was running in just one-direction. The mechanism of winding foil EDS was based on a steady tool wear model of the running foil which enabled a stable slicing process. Analysis of the tool wear model at steady state showed that the tool wear length in winding foil EDS was decided by the tool wear ratio, foil running speed and workpiece width. The development of the new experimental system of the winding foil EDS method was described and the machining stability of this method was presented. The performances of winding foil EDS of SiC such as slicing speed, kerf width etc. were described. In addition, the influences of flushing effect on the winding foil EDS performance were investigated. Both higher foil running speed and flushing can contribute to improve the slicing speed. An average kerf width of around 95μm was achieved by this method with foil tool electrode thickness of 30μm.

In Chapter 5, development of multi-discharge EDM of SiC by electrostatic induction feeding method is described. Aiming to improve the productivity of foil EDS, multi-foil electrical discharge slicing of SiC was proposed. In the multi-wire EDS method which is being widely developed for slicing SiC ingot currently, a single wire is wound multiple turns and the electricity is fed to each winding turn of the wire electrode at the same time. Multi-discharge is realized by introducing a large impedance into each branch of discharge circuit so that the electrical potential at each wire electrode will not be easily affected by the occurrence of one discharge at a certain wire electrode. However, introduction of large impedance brings about low energy efficiency due to the consumption of electric energy of the resistance. Besides, large impedance (mainly inductance X_L) in the discharge circuit makes it difficult to generate discharges with short pulse duration which is considered necessary to perform high accuracy and efficiency slicing of SiC. In conclusion, this method is still under developing. On the other hand, EDM by the electrostatic induction feeding (EIF) method, in principle, can realize multiple discharges with an extremely simple discharge circuit (no resistance is required in the discharge circuit). In addition, in this method, only a bipolar pulse power supply is required to realize multiple discharges at the same time. Non-contact feeding of electricity can also be achieved by the electrostatic induction feeding if necessary. Therefore, the challenge of applying this method to multi-discharge EDS of SiC was proposed in this study. However, due to the limited conditions in developing the multi-foil EDS system, experimental setup of multiple-discharge EDM coring of SiC ingot was developed instead to investigate the proposed multi-discharge EDM method. The development of the new experimental setup was described and the machining experiments were presented. The multi-discharge EDM coring experiments were performed successfully. With six sets of separate tool electrodes, six discharges were generated simultaneously or sequentially in a single pulse of the pulse power supply. The discharge frequency was increased to several times of the frequency of the pulse power supple. The machining rate of multi-discharge EDM by EIF could be increased by increasing the pulse power source frequency and the number of separate feeding capacitors. Moreover, compared with the conventional single-discharge EDM by the electrostatic induction feeding method under the same total discharge energy, both the machining efficiency and the machining accuracy could be improved by the multi-discharge EDM by EIF due to the separate feeding of electricity. It is therefore considered that the same method and principle can be applied for multi-foil EDS method.

In Chapter 6, the main findings obtained in Chapter 2 to Chapter 5 are summarized as the final conclusions of this thesis. The remaining research subjects and the perspective of the future research work are described based on this research.