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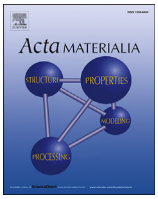

Full length article

Atomic-scale characterization of subsurface damage and structural changes of single-crystal silicon carbide subjected to electrical discharge machining

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ABSTRACT

Single-crystal silicon carbide (SiC) is an important semiconductor material used in power electronics. Due to its high hardness and brittleness, SiC is very difficult to machine using mechanical methods. Electrical discharge machining (EDM) has recently garnered extensive research interest as a potential machining method for SiC. However, this technique induces severe subsurface damage on the workpiece. To date, mechanisms leading to EDM-induced subsurface damage in SiC have not been clarified. This study aims to investigate the atomic-scale subsurface damage in SiC induced by EDM using Raman spectroscopy and transmission electron microscopy (TEM). In cross-sectional TEM observations, three regions of subsurface damage were identified, namely, the re-solidified layers, heat-affected zones, and microcracks. It was found that SiC decomposed into silicon and carbon in the re-solidified layers, and the degree of decomposition depended on the discharge energy and workpiece polarity. The re-solidified layer was a mixture of crystalline/amorphous silicon, crystalline/amorphous carbon, and nano-crystalline SiC. The presence of an extremely thin graphite layer was observed in the re-solidified layer. The heat-affected zone remained crystalline but showed a different crystal structure distinct from that of the bulk.

1. Introduction

Single-crystal silicon carbide (SiC) is a hard and brittle material with high melting and boiling points. Due to its excellent physical, chemical, and electrical properties, such as high thermal stability, resistance to corrosion, and wide bandgap, SiC has become an important candidate material for applications exposed to high temperatures pressures, as well as corrosive environments. Owing to its wide bandgap, SiC also has the potential to replace silicon in high-power applications. The demand for SiC devices is predicted to rise rapidly in the near future. Ultraprecision machining of SiC is an essential step to ensure quality, reliability, and cost efficiency for SiC-based device manufacture, and is becoming increasingly important when the above technology trends are considered.

However, owing to its high hardness and brittleness, SiC is extremely difficult to machine using conventional methods such as mechanical polishing. On the other hand, SiC is electrically conductive, implying it can be finished by electrical machining methods. As a nonconventional machining technology, electrical discharge machining (EDM) has recently garnered research interest as a potential precision machining method for SiC. EDM does not involve mechanical contact between the tool and workpiece, and is therefore less affected by the workpiece hardness and brittleness.

Slicing of SiC ingots to produce thin wafers using wire-EDM (WEDM) has been an active area of research in recent decades. Kato et al. [1] compared the processes of WEDM slicing and diamond wire sawing of SiC ingots and concluded that WEDM achieved lower surface roughness but produced damaged layers containing SiO_2 and graphite. Yamamoto et al. [2] investigated the cutting of SiC ingots using a rotating WEDM slicing method and achieved a large kerf loss and improved surface roughness (3.4 μm Ra). Itokazu et al. [3] performed multi-wire EDM on a polycrystalline SiC ingot and achieved satisfactory thickness variation. Yamamoto et al. [4] used a fluorine-based dielectric fluid in the WEDM of single-crystal SiC and concluded that improvement of surface roughness and kerf loss was achieved. Zhao et al. [5]

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conducted EDM on single-crystal SiC ingots using a tensioned copper foil as an electrode for slicing, and concluded that this slicing technique performed better than the WEDM wafer slicing. Ishikawa et al. [6] compared the surface quality induced by fixed and loose abrasives wire cut with wire-EDM and found that the crystal lattice distortion produced by EDM was smaller than that by abrasives wire cut.

Despite the aforementioned advantages, a few problems still remain in the EDM of SiC. One is that EDM causes severe subsurface damage to SiC workpieces. A thick re-solidified layer and thermally induced microcracks will remain on the surface after EDM. Multiple subsequent polishing processes are required to remove the subsurface damage, but polishing is extremely time consuming. In light of this, understanding the subsurface damage and microstructural changes in SiC caused by EDM is essential for developing new processes for damage removal.

The main objective of this study is to investigate the subsurface damage induced by EDM. The emphasis is placed on characterization of the atomic-scale microstructural changes in SiC subjected to EDM. Elucidation of these microstructural changes will provide insights into the physics underlying the EDM of SiC, and enable process optimization for improving surface integrity.

Murray et al. [7] used transmission electron microscopy (TEM) and Raman spectroscopy to characterize the subsurface damage of single-crystal silicon caused by EDM, and found amorphous and crystalline silicon phases as well as subsurface cracks in the damaged layer. As single-crystal SiC has distinctly different material properties from silicon, the response of SiC to EDM might be different from that of silicon. However, to date, there has been no report in literature on the atomic-scale microstructural changes of SiC upon EDM. In the present study, TEM and Raman spectroscopy will be used to investigate the mechanisms causing atomic-scale subsurface damage to single-crystal SiC subjected to EDM.

2. Experimental procedures

2.1. Material

The workpiece used in this study was an *n*-type single-crystal 4H-SiC wafer with a surface plane of (0001). The wafer was 50 mm in diameter and 0.36 mm in thickness, with a chemo-mechanically polished finish. The 4H-SiC has a hexagonal structure with lattice constants of a = 3.073 Å and c = 10.053 Å. The main properties of the SiC workpiece are summarized in Table 1.

2.2. EDM setup and experimental conditions

EDM tests of single-crystal SiC were conducted on a RC-type EDM machine MG-ED72. As shown in Fig. 1, pulse generation of the RC-type EDM depends on the charging and discharging capacitors in the generator circuit. The EDM system uses a servo controlled machining system. The on-time/off-time of the electrical discharge pulse is controlled by the capacitor in the RC-circuit. A sintered polycrystalline diamond (PCD) rod (diameter 1.0 mm, diamond grain size 0.5 μm) was used as a tool electrode. As demonstrated by Yan and Tan [8], the PCD tool electrode has a very low wear rate and enables subsequent grinding after EDM for subsurface damage removal.

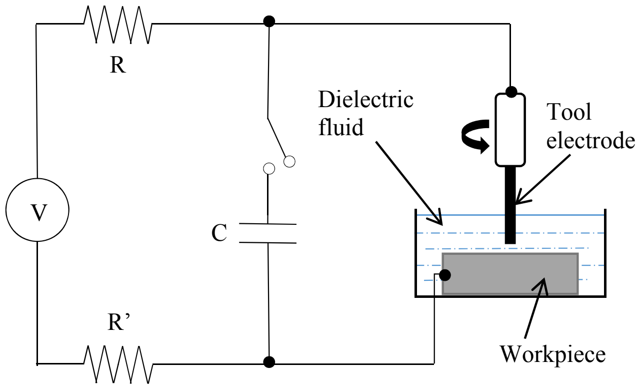

Fig. 1. Schematic diagram of the EDM experimental setup.

In this study, single-discharge and multiple-discharge machining tests were performed. Single discharge tests were performed to study the effect of discharge energy on crater generation by Raman spectroscopy, while multiple discharge tests were performed to create a sufficient surface area with a re-solidified layer for TEM analysis. In multiple discharge tests, grooves that were 1800 μm in length, 1000 μm in width, and 50 μm in depth were machined. The EDM conditions and the properties of the PCD electrodes are summarized in Table 2, and the corresponding discharged energy per pulse in Table 3.

2.3. Surface/subsurface characterization

Field emission scanning electron microscopy (FE-SEM, JEOL JSM-7600F) was used to observe the surface structures of the EDMed workpiece, and material compositions were characterized using an energy dispersive X-ray spectroscopy (EDS) system (Bruker AXS). A Taylor Hobson CCI type white-light interferometer with a 50 × objective lens was used to measure the surface topographies of the discharge-induced craters. The surface profile and crater depth were quantitatively measured with the assistance of the commercially available software TalyMap Platinum 6.2.

Laser micro-Raman spectroscopy was conducted at the centers of the electrical discharge induced micro-craters using a JASCO NRS-3100 Raman spectrometer to identify possible phase transformations in SiC. The excitation source used was a solid-state

Table 1
Properties of the SiC workpiece.

Property item	Value
Workpiece material	4H-SiC
Surface plane	(0 0 0 1)
Doping type	*n*-type
Electrical resistivity, [Ω·m]	1.3–2.5 × 10^{-4}
Mohs hardness	~9
Thermal conductivity, [W/(m·K)]	370
Melting point, [°C]	2730
Sublimation temperature, [°C]	2830
Dielectric constant	9.76
Band gap, [eV]	3.26

Table 2
EDM conditions.

Parameter	Value
Input voltage, *V* [V]	70, 80, 90, 100, 110
Capacitance, *C* [pF]	3300
Polarity	Tool (+/−), Workpiece (−/+)
Tool electrode	Polycrystalline diamond (PCD)
Tool diameter, [mm]	1.0
Diamond grain size, [μm]	0.5
Binder (Co) concentration [%]	90
Electrical resistance, [Ω·m]	1.5 × 10^{-2}
Tool rotation rate [rev/min]	~3000
Dielectric fluid	Casty EDM oil