Characterization and Enhancement of a Multi-Layer Diamond Tool for Self-Sensing of Cutting Temperature

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The high-sensitivity and accurate monitoring of micro-zone cutting temperature is crucial for the characterization and optimization of the machining states in ultra-precision cutting process. Using the cutting tools itself as cutting temperature sensors is an innovative method for in-process measurement of cutting temperature. In this work, optimized synthesis process for a multi-layer diamond tool functional of temperature-sensing were proposed. The annealing treatment under high pressure conditions were conducted to promote the diffusion and ionization of boron multimers in the boron-doped diamond zone of the multi-layer diamond, thereby enhancing the crystal quality and semiconductor electrical properties. The improved multi-layer diamond after grinding, as the temperature-sensing cutting tool, was employed for in-process cutting temperature measurement in single-point diamond turning of silicon at different cutting parameters. Results indicate that the capability of the multi-layer diamond tool to in-process accurately monitor cutting temperature during steady cutting process. These insights are pivotal for controlling cutting temperature and refining the ultra-precision cutting process.

1. Introduction

Precise online measurement of cutting temperature is critically important in cutting processes characterized by thermo-mechanical coupling. It can be employed to characterize cutting states, monitor the surface quality of the machined workpiece, and evaluate tool wear [1, 2]. Unlike cutting forces, current mainstream methods for measuring cutting temperature, such as infrared thermography and thermocouples, face limitations in sensitivity and spatial resolution, particularly in micro/nanoscale ultra-precision machining [3, 4]. These methods struggle to accurately measure the temperature at the tool-chip interface due to the constraints of their measurement principles. In 2021, Uhlmann et al. proposed a novel boron-doped diamond tool, utilizing the inherent negative temperature coefficient thermosensitive properties of boron-doped diamond material for direct temperature measurement in the micro cutting zone, without the need for additional sensors [5]. In 2023, the authors further improved the boron-doped diamond tool material by introducing a boron-hydrogen co-doping strategy, significantly enhancing the sensitivity and measurement range of boron-doped diamond tools for cutting temperature sensing [6]. Following this, the authors proposed a multi-layer diamond tool, wherein a thin layer of boron-doped diamond (BDD layer), functioning as a temperature sensor, is embedded within the diamond tool. This approach effectively improves the response and resolution of temperature measurement by reducing the volume of the temperature-sensing layer [7]. However, the heavily doped boron regions in the BDD layer within the multi-layer diamond tool tend to suffer from boron clustering, causing lattice distortion that limits their use in ultra-precision cutting applications.

In this work, we propose a high-pressure annealing process for the multi-layer diamond tool materials that significantly mitigates boron clustering in the boron-doped regions. This process improves the overall lattice quality and mechanical performance of the diamond tool. The optimized diamond tool was applied in single-point diamond turning of single-crystal silicon, enabling precise online temperature measurement in the micro cutting zone.

2. Methods and Results

2.1 Multi-layer diamond tool for cutting temperature sensing

By substituting boron atoms into the diamond lattice, single-crystal diamond can be transformed from an insulator into a p-type semiconductor [8]. Boron-doped diamond exhibits an inherent negative temperature coefficient thermosensitivity, making it suitable for use as a temperature sensor. As illustrated in Fig. 1, a multi-layer diamond tool is composed of two layers of single-crystal diamond (SCD layers) and one sandwiched layer of boron-doped diamond (BDD layer). The upper SCD layer is finely polished into a nanoscale cutting edge, capable of precise material removal. The BDD layer functions as a cutting temperature sensor, with the boron doping concentration significantly influencing its semiconductor electrical properties as a temperature sensor. While the boron doping concentration must be sufficiently high to ensure low internal resistance and minimize self-heating effects, excessive boron doping can lead to the formation of boron clusters within the diamond lattice [9]. These clusters induce lattice distortions, negatively impacting the mechanical properties of the diamond. Furthermore, the presence of boron clusters exacerbates carrier scattering within the diamond lattice, reducing carrier mobility [10]. Therefore, an optimized synthesis process for multi-layer diamond tools is required to mitigate boron clustering within the diamond lattice. This optimization is crucial for enhancing both the mechanical performance of multi-layer diamond tools and their capability for accurate temperature measurement.

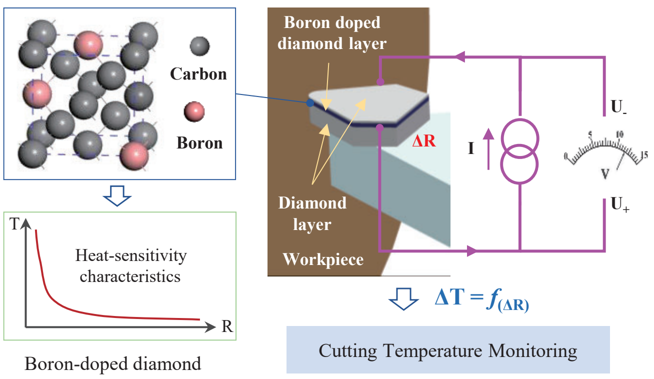

Fig. 1 Principle of cutting temperature measurement using multi-layer diamond tools

2.2 High-pressure anneal heat treatments for multi-layer diamond tool

High-pressure annealing is a critical method for the thermal treatment of diamond, capable of significantly altering the distribution and configuration of impurities within the diamond lattice [11]. Fig. 2 (a) shows the optical appearance of a multi-layer diamond sandwiched with a BDD layer with a boron doping concentration of 1000 ppm and a thickness of 100 μm, both before and after high-pressure annealing. The annealing process was conducted under high-temperature and high-pressure conditions (1960°C, 2.5 GPa) for 3 hours. This extreme high-pressure environment was employed to suppress the graphitization of diamond. As depicted in Fig. 2 (a), the original multi-layer diamond exhibited numerous boron clusters within the BDD layer, attributed to boron polyatomic complexes induced by heavy boron doping. These clusters were eliminated following high-pressure annealing, indicating that this treatment facilitates the redistribution and reconfiguration of boron within the diamond. Additionally, as shown in Fig. 2 (b) and (c), micro-Raman spectroscopy measurements were performed on two micro-regions labeled A and B on both the original and annealed diamond samples. In the original sample, Raman peaks were observed at 500 cm^{-1} and 1220 cm^{-1}, associated with boron dimer configurations (-B-B- or -B-C-B-) [12]. In contrast, these peaks were absent in the annealed sample, where new peaks at 590 cm^{-1}, 900 cm^{-1}, and 1040 cm^{-1} were observed, corresponding to changes in the phonon density of states in diamond induced by boron doping. This suggests isolated boron substitutional doping and the resulting shallow-level excitations in the diamond lattice [13]. Furthermore, compared to the original BDD sample, the diamond peak at 1332 cm^{-1} shifted to higher energy and exhibited a reduced full width at half maximum (FWHM), indicating a reduction in lattice stress and contraction due to high-pressure annealing [14]. Changes in the semiconductor doping state can impact its electrical properties. Hall effect measurements (detailed in Fig. 2(d)) revealed a significant increase in carrier concentration and mobility, along with a decrease in resistivity in the BDD layer of the multi-layer diamond after high-pressure annealing. This is a result of the dispersion of boron clusters, enhanced boron ionization, and reduced carrier scattering post-annealing.

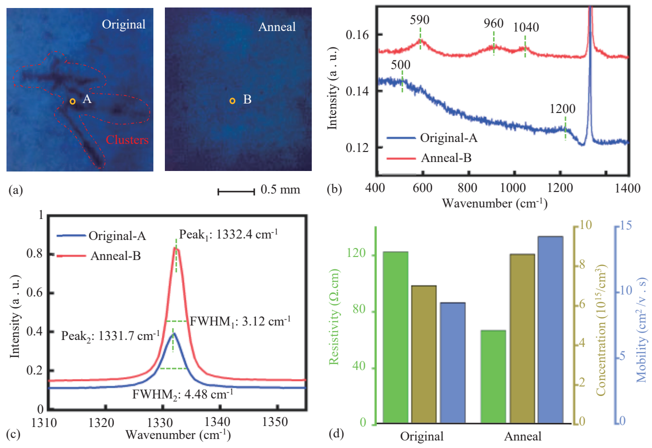

Fig. 2 Characteristics of multi-layer diamonds after high-pressure anneal treatment, (a) optical appearances; (b) and (c) micro-zone Raman spectroscopy measurements; (d) Hall effect measurements

2.3 Cutting temperature online measurements using multi-layer diamond tool

The multi-layer diamond, after high-pressure annealing, was ground into an ultra-precision cutting diamond tool, as shown in Fig. 3. The tool has a rake angle of 0°, a clearance angle of 6°, a tool nose angle of 90°, and a cutting edge radius of approximately 40 nm. The tool was connected via silver wires to a resistance signal acquisition circuit. Conductive silver adhesive was used to connect the silver wires to the diamond tool to ensure ohmic contact. The circuit mainly includes: a 10 μA constant current source module, providing a steady microcurrent to the BDD layer of the multi-layer diamond tool, a signal amplification and filtering module for the voltage of the BDD layer, and a micro controller module with Bluetooth wireless transmission for the acquisition of voltage signal. These modules are powered by a 3.7 V lithium battery.

Prior to conducting cutting temperature measurement experiments, the relationship between the micro-region temperature near the multi-layer diamond tool edge and the resistance of the BDD layer of the multi-layer diamond tool was calibrated, following the methodology and process described in reference [6]. As illustrated in Fig. 4 (a), the multi-layer diamond tool setup was installed on an ultra-precision single-point diamond turning machine to perform the subsequent online monitoring experiments of cutting temperature. The workpiece was a single-crystal silicon sample with a diameter of 120 mm. The spindle speed was set at 250 rpm, with a feed rate of 10 μm/s and a cutting distance of 3 mm. It is noted that the cutting experiments were conducted without the use of compressed air or coolant. Fig. 4(b) depicts the relationship between the cutting temperature and the cutting depth during the end face turning of the single-crystal silicon sample. The cutting depth was varied in 1 μm increments, ranging from 1 μm to 4 μm. As shown in the figure, as the cutting depth increased from 1 μm to 4 μm, the steady-state cutting temperature rose from 40.4°C to 136.7°C. This increase can be attributed to the greater material deformation and the increased friction at the tool-chip interface under larger cutting depths, leading to more heat generation. Additionally, at cutting depths of 1 μm and 2 μm, the cutting temperature rapidly increased at the beginning of the cutting process and quickly reached thermal equilibrium, thereafter exhibiting minor fluctuations within a narrow range. In contrast, at cutting depths of 3 μm or 4 μm, the cutting temperature increased rapidly at the start, but then continued to rise incrementally. It began to stabilize after 300 seconds of cutting process. This behavior may be due to the differing proportions of brittle-ductile cutting deformation domains in single-crystal silicon under varying cutting depths.

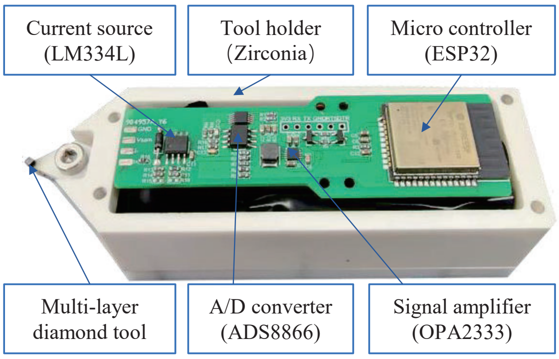

Fig. 3 Multi-layer diamond tool setup for cutting temperature measurement

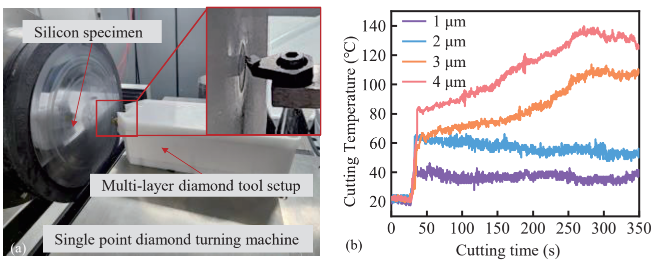

Fig. 4 (a) cutting experiments setup; (b) measured cutting temperature in end face turning of silicon

3. Conclusions

In this work, an improved synthesis process for multi-layer diamond tools with a temperature-sensing BDD layer was proposed to achieve higher sensitivity and faster response in cutting temperature monitoring. High-pressure annealing was employed to promote the dispersion and ionization of boron polyatomic complexes within the BDD layer of the multi-layer diamond, significantly enhancing the lattice quality and semiconductor electrical properties. The cutting temperature measurement capability of the multi-layer diamond tool was validated through ultra-precision single-crystal diamond turning experiments of single-crystal silicon. The experimental results demonstrated that the optimized multi-layer diamond tool can perform highly sensitive online monitoring of the micro-region cutting temperature without the need for additional temperature sensors.

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