The direct measurement of cutting temperature in micro zone using a boron-doped diamond tool

Shiquan Liu[1], Liang An[1], Yuan-Liu Chen[1#]
1 State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, 310027 Hangzhou, China
Corresponding Author / Email: yuanliuchen@zju.edu.cn, TEL: 0571-87952294

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The thermal state of micro cutting zone in ultra-precision machining significantly affects the surface profile accuracy and tool wear intensity. The temperature of micro cutting zone near tool edge is difficult to directly measure due to the limitation of the low spatial resolution of the additional sensor. This paper presents a new cutting temperature measurement method, in which the cutting tool itself was as a function of temperature sensor for temperature measurement in the micro cutting zone. The self-sensing temperature of cutting tool was realized by the heat-sensitive characteristics as P-type semiconductor of diamond tool with boron doping. Equipped with the high-sensitivity signal acquisition and the high-spatial resolution function calibration method between resistivity and temperature, the cutting temperature self-sensing tool realized the online measurement of cutting temperature at tool edge in the single-point diamond turning processing of silicon.

1. Introduction

Single point diamond turning (SPDT) is a crucial technique employed in the manufacturing of micro-structured or freeform surfaces [1]. Among the measurable parameters during the process, cutting temperature serves as a valuable indicator due to its association with tool wear and surface defects caused by temperature-induced chemical processes [2]. Consequently, high spatial resolution and sensitivity are required for accurate cutting temperature measurement in SPDT.

Several existing methods can be utilized for in-process cutting temperature measurement. Infrared thermography, for instance, enables the non-contact acquisition of the 3D temperature field of the cutting tool or the machined workpiece surface [3]. However, accurately measuring the temperature at the cutting edge of the diamond tool becomes challenging due to the obstruction caused by cutting chips generated during the turning process [4]. Thermocouples and thermal resistors are two types of contact sensors widely employed in cutting temperature measurement due to their wide measuring range and high accuracy [5]. However, these methods rely on additional sensors that cannot be positioned too close to the cutting micro-zone, resulting in measured temperatures that differ from those at the cutting edge [6]. Recent work by E. Uhlmann introduced a cutting temperature measurement method using a boron-doped diamond tool synthesized via chemical vapor deposition (CVD) [7]. This approach, which employs the diamond tool itself as the temperature sensor, provides a promising means of accurately obtaining temperatures within the cutting zone of the tool.

In this paper, we propose a new method to measure cutting temperature using boron-doped diamond tool as a cutting temperature sensor in SPDT. The thermal properties and lattice structure of boron-doped diamond were analyzed through first-principles simulations. The diamond with a boron doping dopant of 2 wt.% under high temperature and high-pressure condition were synthesized, enabling it to serve both as the temperature sensor and the ultra-precision cutting tool. Experimental results were obtained to demonstrate the effectiveness of the proposed method for cutting temperature measurement in SPDT.

2. Method and setup

2.1 The principle of cutting temperature measurement

Fig. 1 depicts the schematic of the cutting temperature measurement principle using a boron-doped diamond tool. Boron dopants introduced into diamond enable it to function as a P-type semiconductor, wherein a shallow acceptor level is generated and hole carriers migrate within the diamond lattice. Leveraging the negative temperature coefficient heat-sensitive characteristics exhibited by the boron-doped diamond as a P-type semiconductor, temperature sensing capabilities are achieved through calibration of the resistance-temperature relationship. The boron-doped diamond, when engineered into a diamond tool with a sharp cutting edge, allows for cutting temperature measurement within the cutting micro-zone.

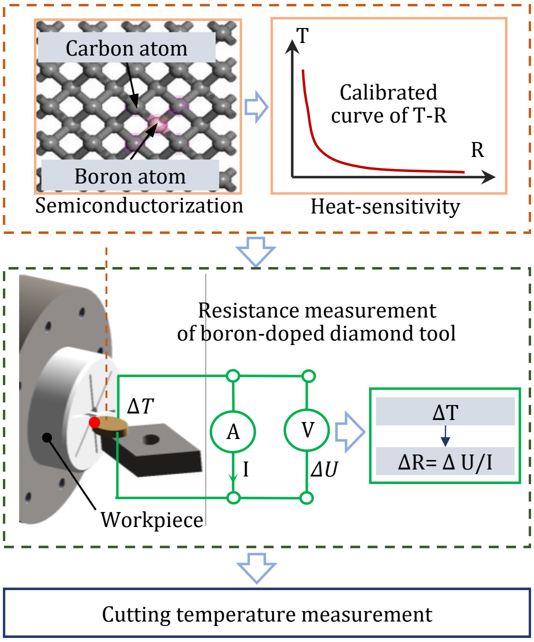

Fig. 1 Principle of cutting temperature measurement using the boron-doped diamond tool

2.2 First principles simulation of diamond with boron doping

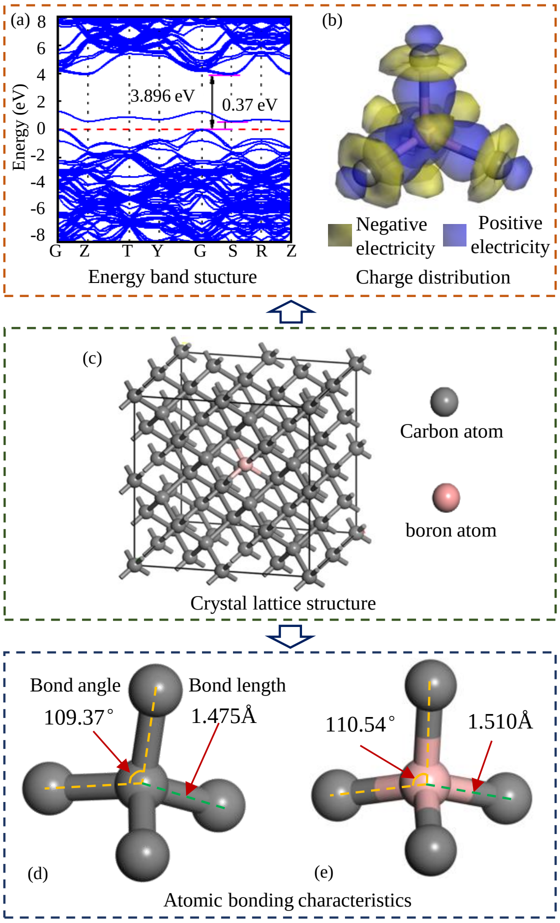

Fig. 2 First principles simulation of diamond boron doping

In order to evaluate the semiconductor properties and doped crystal quality of boron-doped diamond, initial doping compositions were simulated using the first-principles method based on density functional theory (DFT) with a plane-wave ultrasoft pseudopotential approach. The simulations were performed using the castep module of the Materials Studio software. The model employed a 2x2x2 supercell of diamond containing 64 atoms, with boron atoms doped into the diamond lattice via substitutional single atom incorporation as depicted in Fig. 2 (c). The band structure and differential charge distribution of boron-doped diamond are shown in Fig. 2(a) and Fig. 2(b), respectively. This indicates that due to boron doping, the band gap of diamond is reduced to 3.896 eV, and an impurity level appears 0.37 eV above the valence band. Charge transfer exists between boron and carbon atoms, with carbon atoms exhibiting electronegativity and boron atoms exhibiting positive polarity, which is a typical electrical behavior of P-type semiconductors. Calculation of the lattice dimensions of boron-doped diamond reveals that the carbon-carbon bond length is 1.475 Å, with a bond angle of 109.37°. The boron-carbon bond length is 1.510 Å, with a bond angle of 110.54°. Therefore, boron doping can induce the P-type semiconductor behavior in diamond, but when selecting the doping concentration, a balance between lattice quality and electrical performance needs to be considered.

2.3 Tool system setup

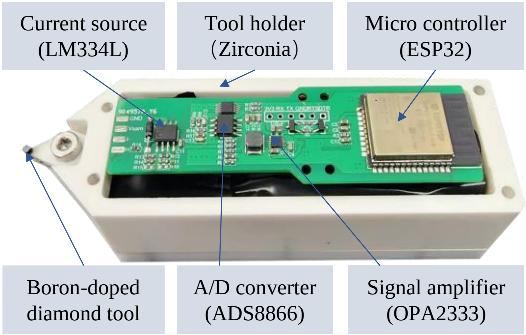

Fig. 3 The boron-doped diamond tool system

The tool system utilized for cutting temperature measurement mainly consisted of two key components, as presented in Fig. 3: the boron-doped diamond tool and a circuit module responsible for signal processing and transmission. The boron-doped diamond was synthesized with a boron doping concentration of 2 wt.% under high temperature and high-pressure conditions. The boron-doped diamond tool was securely attached to a ceramic tool holder and connected to the circuit module through two Pt electrodes. To accurately measure the cutting temperature, it is essential to have a reliable resistance acquisition module for the boron-doped diamond tool. The resistance of the boron-doped diamond tool was measured using the four-wire method. To maintain a constant current of 1 μA, a circuit module incorporated a constant current source based on LM334L. The voltage resulting from the temperature-induced resistance change in the boron-doped diamond tool was amplified using an OPA 2333-based signal amplifier. Subsequently, the signal was digitized by an AD converter built on ADS8866 and transmitted to a PC via a Bluetooth module operating on an STM32 processor.

2.4 Cutting temperature measurement

In order to validate the accuracy of the cutting temperature measurement using the mentioned boron-doped diamond tool, the tool system was installed on a single point diamond turning machine for conducting cutting experiments, as depicted in Fig. 4. A single silicon specimen was employed for the turning process. Throughout the experiments, the spindle rotational speed of the machine was set at 250 rpm, while the feed rate of the tool was set at 20 μm/s.

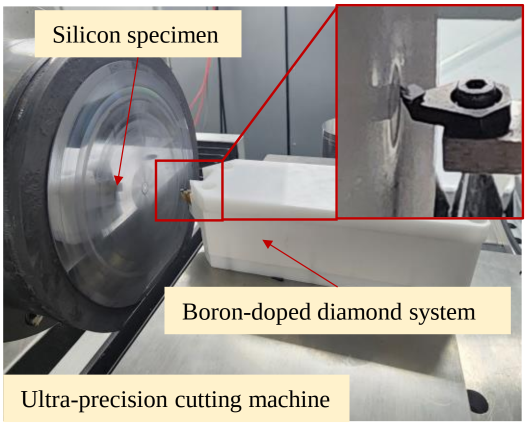

Fig. 4 Experimental setup on a diamond turning machine

Fig. 5 illustrates the relationship between the cutting temperature and the depth of cut during the cylindrical turning of a single silicon specimen. The depth of cut was varied at increments of 1 μm, ranging from 1 μm to 4 μm, in order to investigate the effect of depth of cut on the cutting temperature.

Specifically, at depths of cut of 1 μm or 2 μm, the cutting temperature exhibited a rapid increase at the beginning of cutting and stabilize after reaching a thermal equilibrium. Conversely, at depths of cut of 3 μm or 4 μm, the cutting temperature exhibited an initial rapid rise followed by smaller incremental increases. It reached a maximum value after 300s and remained stable thereafter. Furthermore, as the depth of cut increased from 1 μm to 4 μm, the amplitude of the cutting temperature rose from 40.4°C to 136.7°C. This can be attributed to the increased heat production resulting from larger material deformation and friction caused by the larger depth of cut.

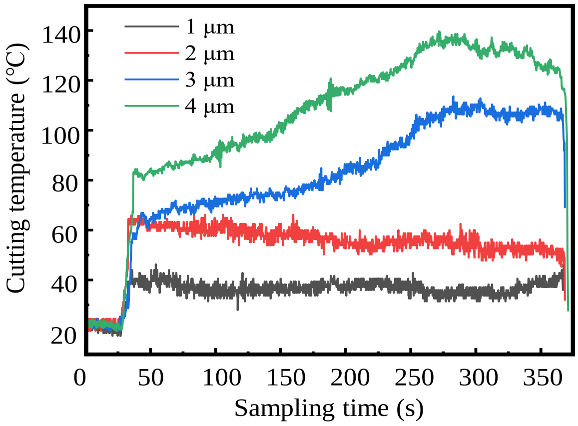

Fig. 5 Measured cutting temperature in turning of single silicon

3. Conclusions

This paper presents a novel approach for measuring cutting temperature in single point diamond turning using a boron-doped diamond tool, without the need for additional temperature sensors. The semiconductor electrical properties of the boron-doped diamond were validated using first principle simulations. The boron-doped diamond was synthesized with a dopant concentration of 2 wt.% under high temperature and high-pressure conditions. To evaluate the performance of the cutting temperature measurement, experiments were conducted using the boron-doped diamond tool to turn single silicon specimens on a diamond turning machine. The results of the experiments confirmed that the proposed system is capable of sensitively measuring the cutting temperature.

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