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Improving machining performance of single-crystal diamond tools irradiated by a focused ion beam

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ABSTRACT

Tool shape is an important factor determining the shape and accuracy of machined areas in ultra-precision machining. Use of a focused ion beam (FIB) is an effective means to fabricate micro- to submicro-scale tool shapes. However, ion irradiation causes doping and defects in the tool that reduce tool performance. To use FIB machining on a single-crystal diamond tool without degrading tool performance, a combination of 500 °C heat treatment and aluminum deposition was used to remove gallium (Ga) ions induced by ion irradiation. The method was evaluated through machining experiments that showed that irradiation of Ga ions causes work materials to adhere to the tool surface. This adhesion and the resulting rapid tool wear were reduced by heat treatment. The proposed method also improved the transcription ability and wear resistance of the tool so it was capable of producing a surface quality better than or equal to that produced by non-irradiated tools, even over long cutting distances.

1. Introduction

The development of micro/nanostructuring technology requires better ultra-precision processing technology. Photolithography followed by etching is the technique most widely used for fabricating micro/nano-scale structures [1,2]. Even so, this method has some drawbacks including being a time-consuming process and requiring complex equipment. Furthermore, the machined material is limited to silicon, glass, and a few other specific materials. Mechanical machining is another effective way to fabricate ultra-precision machine parts and micrometer-scale structures [3,4]. The mechanical method can be used to fabricate structures in various materials and has a high throughput. In mechanical machining, structures are fabricated by transcribing the tool shape, and therefore the shape and accuracy of the tool itself as well as motion the accuracy of the process are important factors in the fabrication process.

A single-crystal diamond tool is generally used in high-precision machining because of its high wear resistance, low affinity, sharp cutting edge, high transcription ability, and other superior characteristics. The shape of the diamond tool is generally formed by mechanical polishing, although achieving complex and minute details is difficult because of the inherent characteristics of the diamond. Use of a focused ion beam (FIB) is an effective means of fabricating micro- to nanometer-scale tool shapes because of its suitability for micromachining [5]. FIB machines target material on a nanometer scale by irradiating gallium (Ga) ions using sputtering. However, this method leads to ion implantation and cause defects in the target material. This changes both the material properties and the machining performance of the tool. Hence, a better method is required to permit FIB machining of ultra-precision diamond tools.

We propose using heat treatment of FIB-irradiated single-crystal diamond tools to improve their machining performance. We investigated the effect of heat treatment on residual Ga ions and the roughness of the irradiated surface. We conducted machining experiments with aluminum alloy and nickel phosphorus (NiP) to investigate the effects of FIB irradiation and the proposed heat treatment on the machining performance of the diamond tool. We used the results to evaluate the effectiveness of the heat treatment.

2. Heat treatment for reducing Ga ions

In micromachining using FIB, the target is irradiated by Ga ions and material removal at a nanometer scale is possible through sputtering. Even though the target material is removed in the

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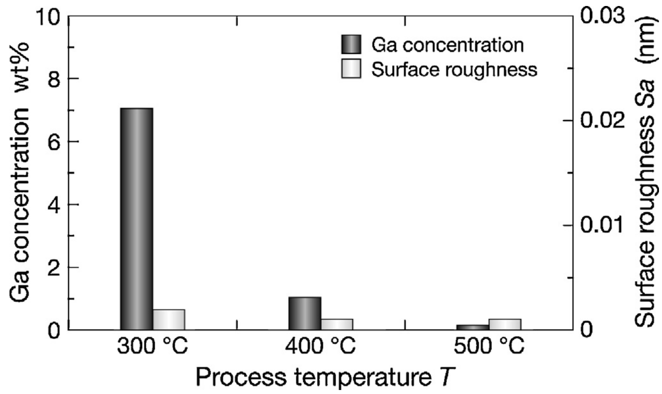

Fig. 1. Changes in the Ga concentration and surface roughness of a single-crystal diamond as a function of process temperature. The diamond surface was irradiated by Ga ions. The irradiated surface was covered with aluminum and then heated.

process, the irradiation results in implantation of Ga ions and defects in the target material. This changes the material properties of the tool, which changes its machining performance. In particular, residual Ga ions may induce increased affinity, which causes a decrease in the transcription ability of the diamond tool. Thus, improving the characteristics of FIB-irradiated tools is important.

This study proposes a process that combines aluminum layer formation with heat treatment to reduce implanted Ga ions. The diamond surface irradiated with Ga ions was covered with an aluminum layer more than 100 nm thick using sputtering. The diamond was heated to temperature *T* and maintained there for 1 h during which Ga ions diffused into the aluminum layer. Then the diamond was cooled and the aluminum layer was removed by a 10 wt% sodium hydroxide solution at 80 °C followed by cleaning in deionized water, isopropyl alcohol, and acetone with sonication.

The relationship between the temperature and the number of remaining Ga ions was measured to investigate the effect of the process temperature. Fig. 1 shows the Ga concentration and surface roughness of the ion-irradiated diamond surface for various process temperatures from measurements made using a scanning electron microscope (SEM, JSN-6510A, JEOL Ltd.) with energy dispersive X-ray spectrometry. To prevent negative influences on the brazing, the maximum process temperature was limited to 500 °C. The diamond surface was irradiated by 30 keV Ga ions at a dose of 10 nC/cm^2 followed by heat treatment at various temperatures. A large amount of Ga remained in the diamond at 300 °C. The number of residual Ga ions decreased as the process temperature increased. The Ga ions in the diamond diffused to the aluminum layer at higher temperature due to the activation. The surface roughness was almost constant for all temperatures and remained approximately the same as that of non-irradiated surfaces. Therefore, heat treatment at high temperatures is an effective way to reduce Ga ions in the diamond.

These results indicate that the number of Ga ions on the diamond surface was reduced by the proposed method without any change in the surface roughness. Heat treatment at 500 °C was appropriate for this process.

3. Machining experiment

3.1. Tool fabrication

Machining experiments were conducted to evaluate the effectiveness of the proposed heat treatment method on FIB-irradiated diamond tools. Single-crystal diamond tools with rounded corner radii of 0.5 mm were used for the experiments. The rake and clearance angles were 0° and 10°, respectively.

Fig. 2 shows SEM images of the tools fabricated for the experiment. The tool rake and flank faces were irradiated by Ga ions at an FIB facility (FB-2100, Hitachi High-Technologies Corporation). The dose was limited to 10 μC/cm^2 to avoid sputtering and maintain the original tool shape. The irradiated areas on the rake and flank faces were 60 μm × 200 μm and 130 μm × 200 μm, respectively. Irradiating these wide areas resulted in the work materials completely contacting with the irradiated area at a depth of cut of several micrometers during the machining process. The irradiated area appears as a whitish area in the SEM image of Fig. 2(b). Fig. 2(c) shows a diamond tool after Ga irradiation and subsequent heat treatment. The irradiated area for this tool also appears, albeit faintly.

Fig. 3 shows the surface topography of the boundary of the irradiated and non-irradiated areas on the rake face measured using a white light interferometer (NewView 7200, Zygo Corporation).

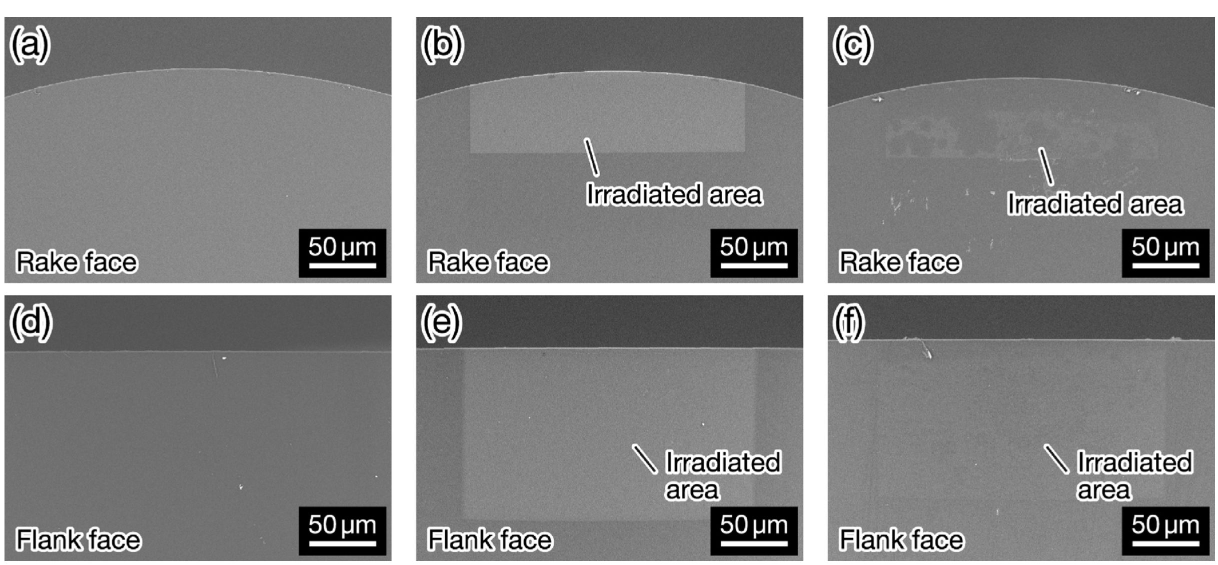

Fig. 2. SEM images of the diamond tool used for the experiments showing (a) rake and (d) flank faces of a non-irradiated diamond tool, (b) rake and (e) flank faces of a diamond tool irradiated with Ga ions at a dose of 10 μC/cm^2, and (c) rake and (f) flank faces of a diamond tool irradiated with Ga ions at a dose of 10 μC/cm^2 and then heat treated.