Precision Engineering xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Development and machining performance of a textured diamond cutting tool fabricated with a focused ion beam and heat treatment

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ARTICLE INFO

Article history:
Received 6 May 2016
Received in revised form 23 July 2016
Accepted 17 August 2016
Available online xxx

Keywords:
Single-crystal diamond tool
Ultraprecision machining
Texture
Friction
Cutting tool
Focused ion beam
Gallium
Heat treatment
Nickel phosphorus
Aluminum alloy

ABSTRACT

This paper presents the fabrication method and machining performance of a textured diamond cutting tool. To improve the machining performance, a texture was fabricated on the rake face of the diamond tool with a depth of 43 nm and width of 1.8 μm by utilizing a focused ion beam (FIB) followed by heat treatment. In addition, a FIB-induced non-diamond phase that adversely affects the machining performance was removed. A machining experiment using aluminum alloy and nickel phosphorus was conducted to evaluate the proposed method. A significant decrease in friction was observed at the tool–chip interface after texturing. This corresponds to a reduced cutting force, which indicates that the machining performance of the tool was improved by texturing. The magnitude of the effect depends on the shape and direction of the texture. The textured tool was able to machine a surface topography similar to that with a non-textured tool, which indicates that the texture effect can be obtained while maintaining the quality of the machined surface by fabricating the texture far from the cutting edge.

1. Introduction

Single-crystal diamond cutting tools are widely used for ultraprecision mechanical machining because of their superior wear resistance, high transcribability, sharp cutting edge, low affinity, and other desirable properties. Mechanical machining can fabricate a spatial resolution structure with high throughput and various material species compared to photolithography. This technique is used to manufacture parts such as optical lenses, molds, and biomedical systems in various industries [1,2]. Despite diamond being the hardest material in the world, diamond cutting tools still experience wear after extensive use or working with other hard materials. This degrades the machined surface quality and shape accuracy. Therefore, improving the performance and efficiency of diamond cutting tools is still an industrial concern.

During cutting, friction at the tool–chip interface is a dominant factor that affects the machinability of the material. Friction is the source of the cutting force, heat, and plastic deformation of the work material; therefore, reducing the friction on the tool surface is an effective way to improve the machining performance.

Adding textured features to a solid surface has been shown to improve the tribological characteristics between surfaces [3–6]. Applying a microscale or nanoscale texture to a surface has been shown to reduce the surface friction by modifying the hydrodynamic pressure, increasing the effectiveness of a lubricant, and other factors. These techniques are effective at improving surface characteristics such as friction and are applied to sliding surfaces.

In past research, we proposed novel cutting tools with either micro- or nanoscale textures on their surfaces to improve their frictional characteristics. A femtosecond laser has been used to create textures on carbide and high-speed steel (HSS) tools, which are primarily used for cutting at the submillimeter or millimeter scale [7–10]. Cutting experiments have indicated that textures with a width of a few tens of micrometers and depth of a few micrometers

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http://dx.doi.org/10.1016/j.precisioneng.2016.09.005
0141-6359/

Please cite this article in press as: Kawasegi N, et al. Development and machining performance of a textured diamond cutting tool fabricated with a focused ion beam and heat treatment. Precis Eng (2016), http://dx.doi.org/10.1016/j.precisioneng.2016.09.005

reduce the friction at the tool–chip interface. Decreasing the friction reduces the cutting force and force fluctuations and enhances the tool life. Thus, this type of tool improve machinability.

A single-crystal diamond tool has a sharp and continuous cutting edge because it lacks any grain boundaries. It is used in ultraprecision cutting. Thus, the shape accuracy of the cutting edge is very important. However, the shape accuracy is slightly less demanding for conventional carbide and HSS tools. The texture fabrication method using the femtosecond laser proposed in past studies [7] has less lateral resolution than the machining size for the diamond tool, which affects the shape of the cutting edge. Therefore, a more effective method is required to fabricate textures on the surface of a diamond tool.

The focused ion beam (FIB) direct milling method is effective for fabricating various microscale and nanoscale shapes. It can also fabricate textures on a diamond surface. However, this method is very time-consuming when used on a diamond. Furthermore, a non-diamond phase with Ga implantation is formed on the irradiated area, which adversely affects the cutting performance of the diamond tool by causing high friction and adhesion and significant tool wear [11]. Therefore, the FIB method is not attractive for fabricating diamond cutting tools.

In this study, we developed a textured diamond cutting tool to improve machining performance. Our method combines a FIB and heat treatment to fabricate micro- to nanoscale textures on the diamond tool surface. A diamond surface irradiated by the FIB is selectively removed by exposure to heated air [12,13]. A concave structure remains after the heating. This technique was applied to fabricate a texture on the diamond cutting tool surface. Cutting experiments using the textured tool were carried out to investigate the fundamental characteristics of the textured tools.

2. Method to fabricate a textured diamond tool surface

2.1. Texture fabrication process

Fig. 1 shows a schematic of the process to texture a single-crystal diamond tool surface by combining FIB irradiation and heat treatment. A carbon layer with a thickness of less than 10 nm is deposited on a single-crystal diamond tool surface to avoid electrostatic charging during FIB irradiation [Fig. 1(a)]. The diamond surface is irradiated with Ga^+ ions by a FIB to form non-diamond phases [Fig. 1(b)]. It is then heated in air at 500 °C to selectively burn away the non-diamond phases and carbon layer (i.e., they are oxidized to CO and CO_2) [Fig. 1(c)]. Finally, the diamond is cooled and then cleaned in ethanol to reveal the texture fabricated on its surface [Fig. 1(d)].

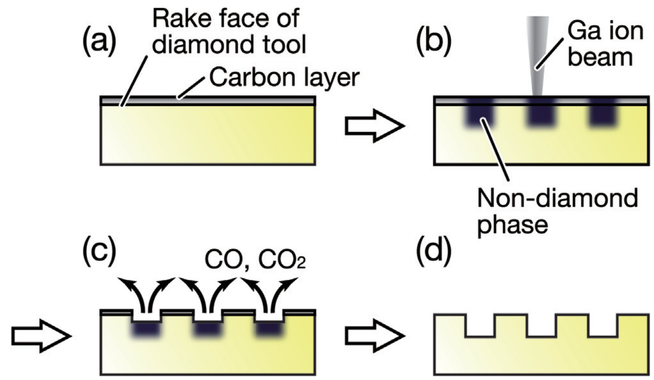

Fig. 1. Method for fabricating textures on a diamond tool surface by using FIB irradiation and heat treatment: (a) deposition of a carbon layer on the diamond, (b) formation of non-diamond phases with FIB irradiation, (c) heating in air to etch the non-diamond phases, and (d) resulting texture on the diamond tool surface.

In this method, structures are fabricated by removing the FIB irradiation-induced non-diamond phases. The resolution and removal rate of the texture are determined by the FIB and heat treatment, respectively. In addition, the non-diamond phase, which adversely affects the machining performance [11], is removed. Therefore, this method can efficiently fabricate sub-micrometer- to micrometer-scale textures with low affected layers.

2.2. Experimental details

A diamond cutting tool with a rounded corner (radius of 0.5 mm) was used for the texture fabrication. The rake and clearance angles were 0° and 10°, respectively. The diamond was Ib type, and the crystal plane of the rake face was {100}. For FIB irradiation, a FIB facility with a gallium liquid metal ion source was used (FB-2100A, Hitachi High-Technology). The heating phase was conducted in an electrical furnace (KM-160, Advantec Toyo Kaisha, Ltd.). The shape of the texture was measured with a scanning electron microscope (SEM) (Miniscope TM-1000, Hitachi High-Technology) and atomic

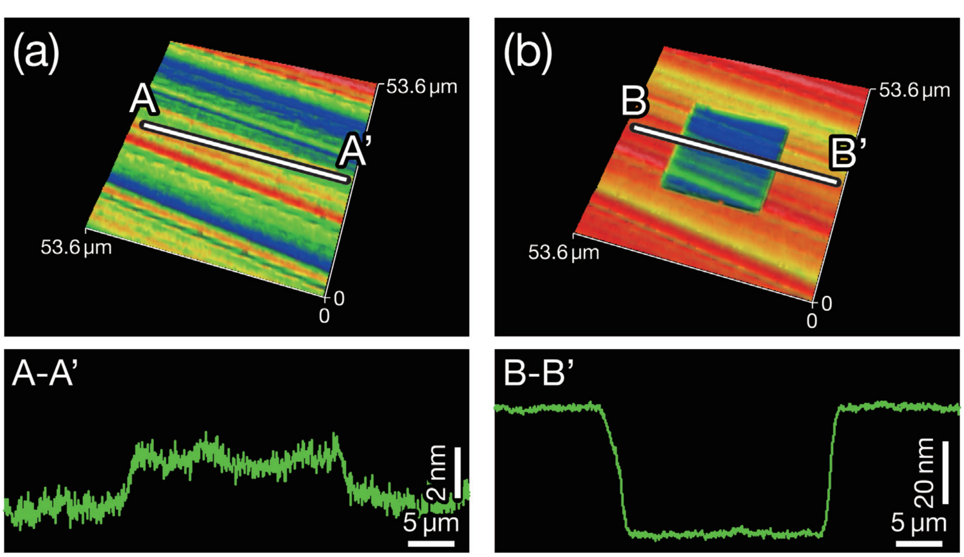

Fig. 2. Patterning on diamond surface by combining FIB irradiation and heat treatment: (a) diamond surface after irradiation of Ga^+ ions at a dose of 10 mC/cm^2 and (b) the same area after heat treatment. Surfaces were measured with a coherence scanning interferometer.