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Microgrooving of a single-crystal diamond tool using a picosecond pulsed laser and some cutting tests

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ABSTRACT

Irradiation of a single-crystal diamond tool was performed with a picosecond pulsed laser to produce a tool with a microgrooved edge. This tool was then used in a metal cutting process to transfer the edge grooves onto a workpiece. Suitable conditions for laser irradiation on the diamond tool were experimentally investigated in terms of groove shape and laser-induced damage to diamond. Two different kinds of cutting experiments were performed; a uniformly grooved surface and a hierarchically structured surface were obtained. The chip formation mechanisms in the metal grooving process were examined. A copper workpiece was rapidly machined the surface of which had microgrooves with a pitch of a few micrometers. An increase of the contact angle was observed on the grooved surface, indicating the improvement of water repellency. This study presents an efficient method to machine microgrooves on metal materials for functional surfaces.

1. Introduction

In recent years, microgrooves have become an increasingly useful surface structure in a wide range of applications. For example, microgrooves have been shown to improve cell alignment, enabling the growth of well-orientated cells for use in tissue repair [1]. In addition, these elongated cells are less adhesive and can be removed from the substrate easily [2]. This increases the survival rate of cultivated cells. They may also protect cells from the detrimental effects of fluidic shear stress and thus allow for the cultivation of sensitive cells [3]. Another example of microgroove use is to control surface wettability. Water repellent surfaces are needed in a broad spectrum of air-cooling applications. Water retention is problematic as it causes a reduction in the air-side heat transfer coefficient, a greater core pressure drop and bacterial growth [4]. Microgrooved surfaces would greatly increase the efficiency of a cooling system. Furthermore, water repellent surfaces are shown to have self-cleaning properties, as water drops will easily roll off the surface [5,6]. A third use for microgrooves can be found in the field of bionics [7,8]. The grooving of implants is particularly difficult as the implant surface is normally curved, and a large surface area needs to be machined. As microgrooves are highly important surface structures, a method to machine them at high efficiency needs to be established.

There are various methods to machine microgrooves, but in order to obtain high form accuracy and low surface roughness, ultraprecision cutting is often used. Moreover, by using a tool servo system or a piezoelectric vibration system to drive a cutting tool, the cutting of microgrooves on three-dimensional shapes, hierarchical structures and complex curved surfaces is possible. However, if the cutting of individual grooves with extremely small pitches is attempted, using a sharp single-point diamond tool, the machining time will become very long and the production cost very high. This would make it difficult to machine large areas.

One possible way to reduce machining time is to use a specially shaped tool with a grooved edge. Multiple grooves on the tool cutting edge would be transferred to the workpiece simultaneously during cutting. In this way, the side flow of workpiece material taking place in individual groove cutting will be suppressed, so that precise groove profiles will be generated without burr formation. However, to make the implementation of this method possible, it is necessary to establish a process to machine microgrooves on the tool. Single-crystal diamond (SCD) is often used as a tool material in ultraprecision cutting. Thus a method to groove SCD is needed.

As an extremely hard and brittle material, SCD cannot be grooved using conventional mechanical methods. Nonconventional machining methods such as focused ion beam machining (FIB) or reactive ion etching (RIE) have been attempted in recent years. FIB uses the collision energy of accelerated ions in order to remove material. It is not only expensive but also has a low material removal rate. This makes it unsuitable for the processing of large areas, such as a long cutting edge. RIE uses ions from a plasma to etch the SCD. This requires a complex and expensive system in order to induce the plasma. RIE is difficult to

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generate curved or slanted surfaces, like V-grooves. In addition, it often results in a high surface roughness due to the ions aggressively interacting with the surface [9]. Thus an alternative method is needed.

SCD can be processed using a pulsed laser [10–14]. The advantages of laser processing are that is relatively low cost, rapid and has high shape controllability. By using a short pulse width, it becomes possible to reduce the heat affected zone (HAZ), which refers to the region where thermal effects are observed, and unwanted phenomena such as thermal stress, material structure change and cracking take place. Irradiation diamond by a nanosecond pulse causes the formation of an amorphous carbon layer with an average thickness of ~2 µm and a HAZ with an average thickness of ~2.5 µm [15]. Some researchers have shown that femtosecond laser machining can be used to drill deep holes in diamond with high shape accuracies [16]. However, a femtosecond laser may result in the problem of intense laser beam self-focusing inside diamond [17]. This is caused by beam filamentation where light propagates through a medium without diffraction, causing self-focusing. Self-focusing produces non-homogeneous graphitized structures, in the form of irregular globules, and therefore deteriorates the machining quality [18]. This effect is lessened for pulse widths longer than 3 ps. From this point of view, a picosecond pulsed laser may be a more suitable choice to machine diamond with limited damage.

A few studies have used lasers to create micro-patterns on the rake face of a tool to reduce cutting force and temperature [19]. The patterns decrease the tool-chip contact area on the rake face. In addition, when the patterns are filled with a solid lubricant, a film forms during cutting and serves as a lubricating film. Micro-arrays have also been machined on diamond to enhance thermal and mechanical performance [20]. Thus, laser irradiation has been shown to be an effective method to improve the performance of SCD tools. However, no attempt has yet been made to machine microgrooves on the cutting edge of an SCD tool.

By using an SCD tool with patterned cutting edge on a commercially available diamond turning machine equipped with a high-speed air bearing spindle to rotate the workpiece, the grooving time for a large-area workpiece can be dramatically reduced compared with the use of a single-point tool. In addition, it becomes possible to machine complex cross-sectional shapes, such as V-grooves, grooves with curved and hierarchical cross sections on a metal workpiece.

Hierarchical grooves have several advantages over uniform grooves. Firstly, they can reduce drag to a greater extent than a uniform structure. An example of this is a bird feather. A feather possesses riblets on its surface; the heights of these riblets decrease towards the edge, creating a hierarchical structure. When compared to a uniform structure, the feather's structure results in a greater drag reduction rate [21]. Secondly, hierarchical structures can also be used to direct fluid flow. Kang et al. reported that uniform grooves are not capable of inducing a directional oil sliding property, so hierarchical grooves are necessary to create directional oil flow [22]. Additionally, hierarchical grooves are not perpendicular to the original surface of the workpiece unlike uniform grooves. This allows for control the color of the metal surface without changing the groove period or size. When light is incident on the grooved surface, a certain wavelength of light is reflected [23]. At different cutting edge angles, different wavelengths of light are reflected, thus altering the surface color and absorption properties of the surface. Not only does this have an aesthetic use, but a practical one such as in solar cell applications were structures are used to enhance ultraviolet absorptivity.

The objective of this study is to investigate the possibility of microgrooving an SCD tool by picosecond laser irradiation and using the grooved tool to establish an efficient method for cutting microgrooves on large-area metal surfaces. By using a picosecond pulse width, it might be possible to reduce the laser-induced damage to the diamond tool cutting edge. In the following experiments, the laser irradiation of an SCD tool was carried out. Then the tool was used in cutting experiments to investigate the possibility of transferring microgrooves from the cutting edge to the metal workpiece surface in an ultraprecision cutting process.

Table 1
Laser parameters.

Laser type	Fibre laser
Wavelength [nm]	1030
Pulse width [ps]	50, 800
Repetition rate [kHz]	100, 300, 1000
Spot size [µm]	6 × 7
Laser fluence [J/cm^2]	4.5, 15.3, 18.5, 26.4, 49.4
Energy distribution	Gaussian

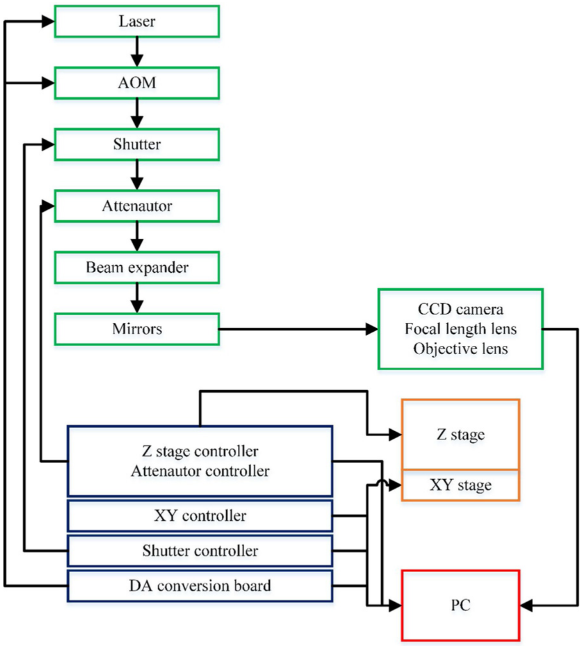

Fig. 1. Schematic of the laser controller system used.

2. Experimental method

The laser used was PFLA-1030TP made by Optoquest Co., Ltd, which incorporates a fiber laser. Irradiation was performed in ambient atmosphere using the parameters shown in Table 1. The laser controller system and the optical system are shown in Figs. 1 and 2, respectively. The laser spot is an ellipse. The laser used has an asymmetric active region and retains this ellipticity throughout the system. Thus the focused spot is also non-circular. The lens used to focus the laser beam on to the stage was M Plan Apo NIR 20X made by Mitutoyo Co. It has a NA of 0.4, and a focal length of 10 mm. The M2 size is < 1.4.

Laser processing was performed on a straight edge SCD tool as indicated in Fig. 3a. The laser was positioned so that the beam center was on the tool cutting edge and the beam was focused onto the rake face of

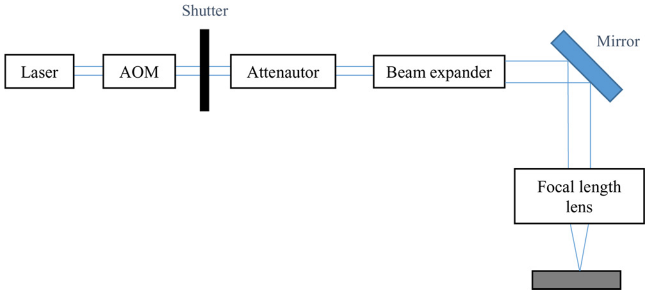

Fig. 2. Schematic of the optical system used.