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# Mechanisms of micro-groove formation on single-crystal diamond by a nanosecond pulsed laser

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## ABSTRACT

Micro-grooves were machined onto a single-crystal diamond surface by laser irradiation with a nanosecond pulse, and the resulting damage was investigated. The causes of four different forms of damage have been identified and examined; cracking, ripple formation, groove shape deformation and debris deposition. Cracking is caused by a rapid temperature change; ripples by interference of the laser reflected from the groove walls; groove shape deformation by enhanced absorption of the laser-induced plasma; deposited ablation debris by two different ablation regimes. Cracking and shape deformation is reduced at the center of the groove, which is very smooth and ripple-free for line irradiations using a single pass. These results provide useful information for reducing the laser-induced damage in diamond and creating damage-free micro-grooved diamond cutting tools.

## 1. Introduction

Micro-grooves have become an increasingly significant surface microstructure in a wide range of fields, especially in bio-medical science. Micro-grooves have been shown to cause cell alignment (Wilkinson et al., 2002), enabling the growth of well-orientated cells for use in tissue repair. Moreover, Korin et al. (2009) have shown that they may protect sensitive cells from the detrimental effects of fluidic shear stress and thus enable the cultivation of sensitive cells. Furthermore, Frenkel et al. (2002) have presented machining of micro-grooves onto the surface of implants (such as joint replacements) as a method to improve osseointegration and thus to lengthen implant life span. Micro-grooves are a highly useful surface texture but they are difficult to machine on specific kinds of materials. Micro-grooves are conventionally processed by photolithography which has given rise to problems such as limited groove geometry, accuracy and usable materials. Laser machining involving the direct irradiation of grooves into a metal surface has also been attempted, but Fasasi et al. (2009) have demonstrated a few problems including groove wall deformation and re-solidification pockets due to melting, as well as a large heat affected zone (HAZ). Alternatively, cutting micro-grooves on metals with a diamond tool is not only more accurate but is also able to reduce the thermal effect compared to laser machining (Yan et al., 2009).

Fabricating micro-grooves on the surface of a diamond tool is also very important. Previous studies have shown that processing micro-grooves onto the rake face of a cutting tool can be effective in improving cutting fluid retention of the tool surface (Sugihara and Enomoto, 2009), reducing the friction force (Obikawa et al., 2011) and the required cutting force (Kawasegi et al., 2009). However, there have not yet been many attempts to make micro-grooves on the cutting edge of a tool. By grooving the cutting edge of tools, it becomes possible to transfer the edge shape onto the substrate surface. The grooved tools can be used to transfer the micro-grooves onto metal materials, making the machining of micro-grooves much more rapid, precise and without burr formation. Unlike the direct fabrication of micro-grooves on metal by laser irradiation, the wall deformation and re-solidification pockets due to melting are not of much concern in the cutting process with a diamond tool.

It is possible to create such a micro-grooved tool using laser irradiation. It is known that diamond transforms into graphite and is ablated by laser pulses. However, it is important to determine the optimal laser parameters in tool processing so as to avoid the generation of a HAZ and subsurface damage (SSD). Eberle et al. (2015) have stated that the HAZ and SSD will cause the tool to exhibit reduced performance, reduced tool life, reduced wear resistance and greater required cutting force.

The laser machining of diamond has been a subject of great interest for the past several decades. Previous studies have estab-

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lished that a femtosecond pulsed laser is more suitable for precision manufacture of extremely small surface structures compared to a longer pulse, as they allow for the use of lower photon energies without loss of precision (Dumitru et al., 2002) or spatial resolution (Preuss and Stuke, 1995). Chichkov et al. (1996) have shown that sharp, well-defined (in other words, damage-free) patterns can be ablated. This is due to the reduced thermal effects of an ultrafast pulse; strong electrostatic ion repulsion force causes break-up of di-electric surfaces, accounting for the nonthermal nature. Furthermore, Stuart et al. (1996) have demonstrated that the ablation threshold is lower for a femtosecond pulsed laser. However, processing costs for a femtosecond laser are much higher and the material removal rate much lower than for a nanosecond laser, especially when machining a deep groove or a large-size structure, like a cutting tool. Thus, to create a micro-grooved tool, a nanosecond pulse would be more appropriate if used along with a damage prevention method. Previous studies discussing the nanosecond laser irradiation of diamond have focused on developing an ablation model (Rothschild et al., 1986), where surface graphitization of diamond is followed by sublimation or reaction. Konov (2012) has reported on the relation between ablation rate and laser fluence and Kononenko et al. (2005) have discussed the laser-induced graphitization of diamond. Despite extensive research on nanosecond pulsed irradiation on diamond, the formation mechanism of the laser-induced damage and the conditions for reducing the damage have not been clarified. Hence, it is important to further address this issue in order to develop methods to prevent damage during nanosecond pulsed irradiation. The ultimate aim of this study is to develop a damage-free method to machine micro-grooves and other micro-structures into diamond to fabricate high-performance cutting tools.

## 2. Experimental method

The laser used in the following experiments was LR-SHG, a Nd:YAG laser pumped by LD, from MegaOpto Co., Ltd. It has a maximum power output of>1W and a pulse width of 15.6 ns at 1 kHz, a wavelength of 532 nm and a spot diameter of 85 μm. For the following experiments, a pulse frequency of 1 kHz was used. The laser output energy has an approximate Gaussian distribution. The laser was controlled using a galvanometer scanner system with a Miramo controller made by YE Data Inc. Laser motion programs were created using GmcLib.DLL 2.0 software and FFFTP software was used to download these programs to the galvanometer scanner system. The laser beam was focused onto a stage using an fθ lens. The diamond used was prepared by chemical vapor deposition (CVD) in rectangular samples with dimensions of $4 \times 3.5 \times 1.12 \pm 0.02$ mm. The surfaces were flat and polished. The irradiated surface was the (100) Miller surface. All the other faces also had an equivalent crystal orientation. The groove depth was measured using the MP-3 laser probe made by Mitaka Kohki Co., Ltd. And the surface structure was observed by the Inspect S50 Scanning Electron Microscope (SEM) made by FEI Company. The atomic structure was identified by a Raman spectrometer (NRS-3100 by JASCO Corporation).

The diamond sample was placed on a base with an opening so that the lower surface was not in contact with the stage surface, as indicated in Fig. 1. As diamond is a transparent material at the laser wavelength used, when the diamond was placed directly onto the stage, the laser energy was absorbed by the stage surface, leaving an irradiation mark on the stage. The heat accumulated by the stage then affected and machined the diamond, also leaving an irradiation mark on the lower surface of diamond. In this case, the laser cannot directly machine the diamond and no meaningful results would be obtained. By using the base, no irradiation marks was produced on the stage or lower diamond surface, showing that the heat absorbed by the stage would not affect the diamond. Line irradiations, 300 μm in length, were performed at a constant scanning speed of 2 mm/s. These line irradiations were first performed with varying laser fluence. Laser fluence was changed in the range of 5.0–8.4 J/cm$^2$. A lower boundary of 5.0 J/cm$^2$ was chosen as an even lower fluence of 4.2 J/cm$^2$ did not produce a clear groove. The lowest fluence was chosen for all the subsequent experiments as it produced the least cracking. The number of passes (or the number of times the line irradiation was repeated) was varied in the range of 2–60 passes. The irradiated surfaces were covered in debris so they were cleaned by being placed in a solution of nitric, sulphuric and perchloric acid (in a volume ratio of roughly 1:5:3) and heated to ∼200 °C. This cleaning process removed the debris and was performed before SEM and laser probe observations.

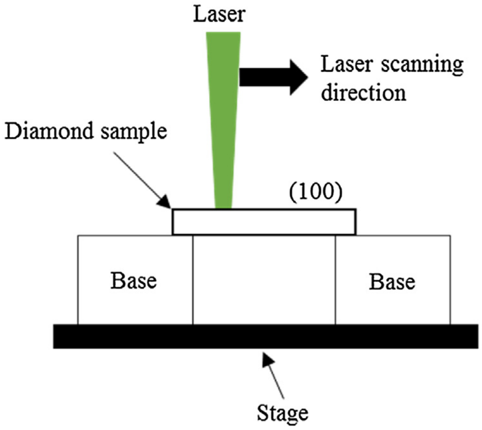

**Fig. 1.** Laser irradiation schematic for micro-grooving on diamond.

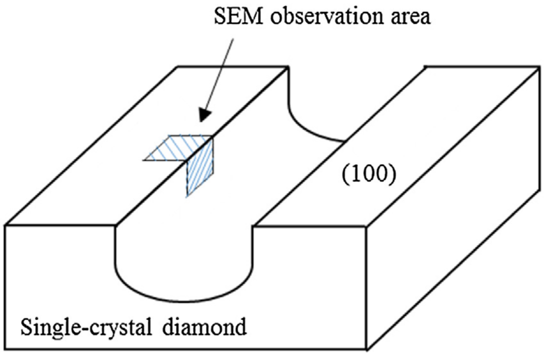

**Fig. 2.** Schematic of SEM observation area on the groove formed by laser irradiation.

## 3. Results and discussion

### 3.1. Cracking behavior

Many cracks were observed on the irradiated surfaces. The schematic for SEM observation is illustrated in Fig. 2. Different sized cracks were formed depending on the laser fluence. As shown in Fig. 3a–d, the cracking region size increased with increasing laser fluence. Upon closer examination, 2 different types of cracks were visible. First, as presented in Fig. 4a, there was a region of wide, open cracks near the groove edge. Second, as shown in Fig. 4b, there were thin straight cracks closer to the center. At the lowest fluence of 5.0 J/cm$^2$, no open cracks were visible; instead, there were thin, bent cracks near the groove edge. It appeared that these cracks were similar in structure to the wide, open cracks due to their position and their lack of straightness. Furthermore, as presented