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High-speed observation of ultrashort pulse laser processing of diamond edge with MHz burst pulses

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Abstract
Diamond possesses exceptional material properties, making it invaluable in fields such as machining, optics, and semiconductors. However, achieving precise and efficient diamond processing remains challenging. Ultrashort-pulse lasers (USPLs) have emerged as a promising solution, offering non-contact operation and minimal thermal damage. Recent studies suggest that burst pulses can reduce surface roughness, yet the removal mechanisms are not fully understood. This study investigates the characteristics of processing of single-crystal diamond (SCD) with USPL and MHz burst pulses. A high-speed camera captured in-process dynamics, while post-process inspections using a laser microscope revealed the resulting surface morphology. Experiments indicated that burst pulses effectively decreased roughness, with per-pulse energy influencing removal rates. Specifically, no significant increase in material removal was observed at per-pulse energy below 8 μJ/pulse, whereas per-pulse energy exceeding 16 μJ/pulse led to increased material removal. Maintaining per-pulse energies above 16 μJ/pulse ensures efficient removal and controlled roughness. This study enhances the understanding of SCD processing with USPL and MHz burst pulses.

Diamond, In-process measurement, Laser, Micromachining

1. Introduction

Due to its outstanding physical properties, diamond has attracted considerable attention in various industrial fields, including tooling, optics, and semiconductors. However, its extreme hardness makes precision machining exceedingly difficult. Conventional diamond machining techniques can be broadly classified into contact and non-contact methods [1]. Among the contact methods, such as mechanical polishing and chemical-mechanical polishing, extensive research has been conducted, and these techniques are widely used in industry. Nevertheless, because these processes rely on abrasive particles to remove material, they present several limitations. For instance, it remains challenging to polish three-dimensional surfaces [2], and crystal orientation can affect wear resistance [3], limiting the achievement of high-precision surfaces to specific conditions. Additionally, these contact-based approaches often result in cracks and subsurface damage, issues that pose significant problems across many applications.

Recently, non-contact polishing techniques (e.g. ion-beam polishing, plasma etching, and laser polishing) have garnered attention as promising alternatives to minimize surface damage on diamonds [4]. Of these methods, laser polishing stands out due to its high efficiency and ability to finish three-dimensional surfaces [2]. For instance, William et al. demonstrated that USPL ablation on polycrystalline diamond achieved a removal rate that was twice as high as that of mechanical polishing [5]. Despite these advantages, achieving high-quality surfaces with laser-based methods remains a critical challenge. In particular, the anisotropic nature of single-crystal diamonds (SCDs) becomes more pronounced under ultrashort-pulse laser (USPL) irradiation, which focuses a large amount of energy in a highly localized region. Pimenov et al. reported that this concentrated energy, especially along the {111} crystal planes, induces structural changes that degrade machining precision [6].

Recent studies suggest that employing burst pulses can help mitigate some of the surface-quality issues associated with ultrafast laser processing. Kiran et al. applied MHz-burst pulses to cylindrical SCDs and observed improved surface quality when the burst parameter N exceeded 5. However, the underlying phenomena and removal mechanisms that occur specifically during MHz-burst processing remain inadequately understood.

Therefore, the aim of this study is to clarify the removal phenomena and mechanisms of SCDs under MHz-burst pulse processing. To achieve this, we perform real-time high-speed camera observations of the removal process, providing insights into the dynamics of material removal and laying the groundwork for further optimization of ultrafast laser polishing methods for diamonds.

2. Experimental methods

Figure 1(a) illustrates the optical setup used for MHz-burst processing under parallel irradiation. A commercial USPL (Light Conversion, Carbide) with a center wavelength of 1030 nm and a pulse duration of 190 fs was used as the laser source. The laser pulses were converted to circular polarization using a quarter-wave plate and were then focused 200 µm beneath the diamond surface with a 5× objective lens (Mitsutoyo, M Plan Apo NIR 5x), as shown in Figure 1(b).

To observe the material removal process, we employed a 20× objective lens (Mitsutoyo, M Plan Apo NIR 20x) and a high-speed camera (Shimadzu, HPV-X2). A secondary laser (center wavelength of 640 nm, pulse width ~20 ns; Cavitar, Cavilux HF) was used for illumination during high-speed imaging.

The sample was an SCD (Element Six), synthesized by chemical vapor deposition. Its dimensions were 6 mm × 6 mm × 0.5 mm, and the laser irradiation plane (the {100} surface) had been mechanically polished. During the experiment, pulse energy E (μJ) and the number of burst pulses N were varied as primary parameters: E was set in the range of 2–80 μJ, and N was varied

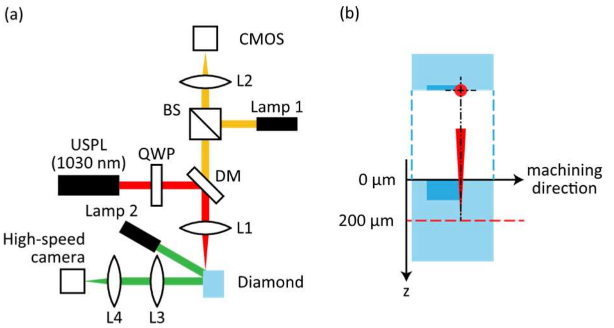

Figure 1. Experimental setup. (a) Schematic diagram of the optical setup for laser processing. BS – beam splitter, QWP – quarter wave plate, DM – dichroic mirror, L1&L3 – objective lenses, L2&L4 – tube lenses. (b) Enlarged view of the machining region. red dashed line – focal plane, blue-shaded area – machined region.

from 1 to 10. All other parameters remained constant. The sample was scanned with a precision stage (Thorlabs, MLS203) at 1.0 mm/s, while the laser (repetition rate: 10 kHz) was irradiated. The scanning process was repeated five times, and each condition was tested four times. After laser processing, the samples were ultrasonically cleaned for four minutes to remove debris. The processed surfaces were then observed and evaluated with a laser microscope (Olympus, OLS5000).

3. Results and discussion

3.1. High-speed observation

Figure 2 shows selected snapshots from the high-speed camera. The red dashed lines indicate the laser irradiation positions. The left column represents the case of N=4, while the right column represents N=8, both at a pulse energy E=32 µJ. As the laser scan progressed, material removal advanced deeper into the sample. Although the total energy delivered to the material was identical for both N=4 and N=8, differences in material removal were clearly observed.

Figure 3 shows the intensity change caused by 10 pulses of laser irradiation during the first scan. This intensity difference reflects the extent of material removal. The results suggest that laser processing was more intense for N=4.

3.2. Microscopic observations

Figure 4 shows the reflected images captured by the laser microscope, along with surface height profiles. The surface roughness and removal volume were calculated based on the

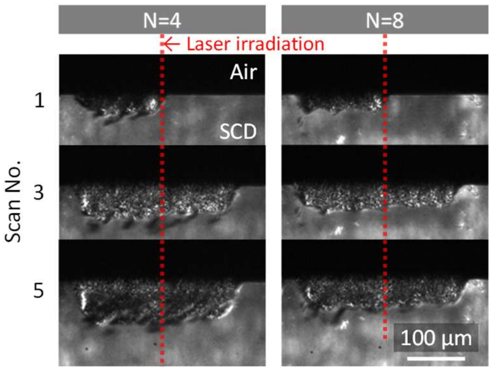

Figure 2. High-speed observation at E=32 µJ. (left–N=4, right–N=8.)

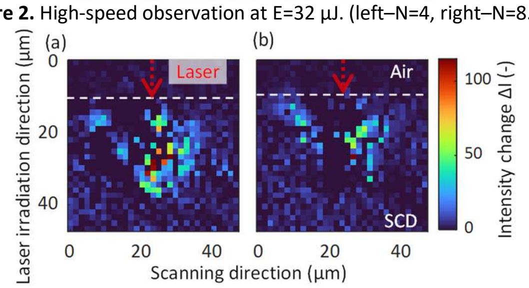

Figure 3. Intensity change at E=32 µJ, when (a) N=4, and (b) N=8.

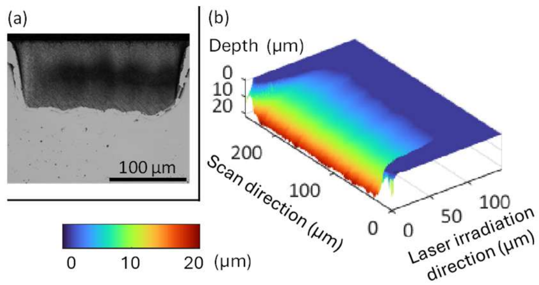

Figure 4. Observation results of the processed surface by laser microscope with E=80 µJ and N=10, (a) brightness, (b) height.

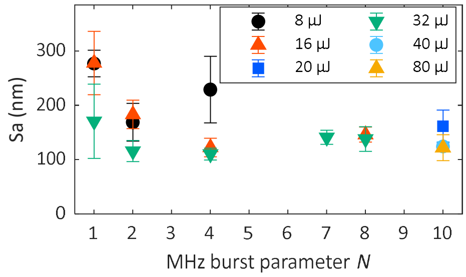

Figure 5. Variation of Sa with respect to burst pulse count *N*.

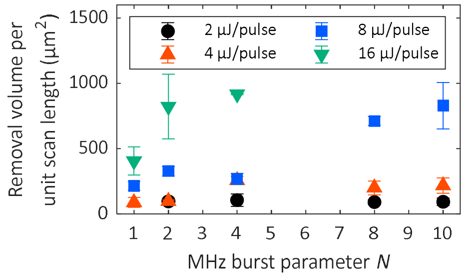

Figure 6. Variation of removal volume per scan length with respect to burst pulse count *N*.

height profiles and are presented in Figures 5 and 6. When N≥2, surface roughness was reduced. A higher surface roughness at E=8 µJ and N=4 can be attributed to insufficient per-pulse energy Ep, which may have caused unstable material removal.

From Figure 6, The removal volume exhibits different behaviors depending on Ep. When Ep<4 µJ/pulse, increasing N does not yield an increase in removal volume. However, at Ep≥8 µJ/pulse, higher N leads to a larger removal volume. This observation, combined with the results of the previous section, suggests that the per-pulse energy influences the mode of material removal.

4. Conclusion

In this study, we investigated the removal process of SCDs using MHz-burst ultrashort pulses by performing in-process high-speed camera observations. Our conclusions can be summarized as follows:

1. Burst processing reduces surface roughness.
2. The mode of material removal varies with the per-pulse energy Ep.

Future work will focus on elucidating the underlying mechanisms responsible for these changes in removal mode and developing processing techniques that leverage these insights to achieve lower surface roughness.

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