# High surface quality micro machining of monocrystalline diamond by picosecond pulsed laser

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In micro machining of monocrystalline diamond by pulsed laser, unique processing characteristics appeared only under a few ten picosecond pulse duration and a certain overlap rate of laser shot. Cracks mostly propagate in parallel direction to top surface of workpiece, although the laser beam axis is perpendicular to the surface. This processed area can keep diamond structure, and its surface roughness is smaller than $R_a$ = 0.2 μm. New laser micro machining method to keep diamond structure and small surface roughness is proposed. This method can contribute to reduce the polishing process in micro machining of diamond.

Laser beam machining (LBM); Laser micro machining; Diamond

## 1. Introduction

Diamond has attracted interest in many applications such as cutting tools [1], heat spreaders and semiconductors [2] because of its high hardness, thermal conductivity and chemical inertness [3, 4]. However, its excellent properties make it difficult to machine by traditional mechanical machining methods, and there are some problems in shaping process of diamond. Scaife machining [5], ion beam machining and laser beam machining have been used to create desired shapes of diamond, but a polishing as finishing process is indispensable to obtain smooth surface. Laser beam machining has high possibility to perform the shape creation process of diamond due to its flexibility and high-throughput compared to other methods. In the polishing process, the surface roughness can be reduced by using diamond abrasives, because diamond cannot be machined without diamond. However, it is an extremely time-consuming process, which leads to the increase of production costs. Thus, in addition to create the shapes by laser beam machining, the reduction of surface roughness is effective to reduce the costs and shorten the total processing time.

It is well known that natural mined diamond has high optical transparency in wide range of wavelength. Artificial diamond is mainly manufactured by two synthesis methods, chemical vapour deposition (CVD) and high pressure high temperature synthesis (HPHT). The lattice defects, which are mainly controlled by nitrogen and boron, result in variation of diamond's transparency. According to the arrangement of nitrogen atoms and the occurrence of boron impurities, artificial diamonds are mainly classified into 4 types (Ia, Ib, IIa, IIb) [6], and Ib type is mainly used in industrial applications. It shows somewhat yellow colour, but there is high transparency in visible wavelength. Around 1 μm wavelength, a lot of industrial lasers are produced, and high average and high peak power can be obtained. The light transmittance ratio of diamond Ib is approximately 70 % around 1 μm wavelength. Although diamond has high optical transparency for a laser beam, stable absorption of laser energy can be achieved by high peak power of pulsed operation, which ignites multi-photon ionization and absorption of laser beam at defects in diamond. Diamond is usually removed by the combination of ablation phenomena, graphitization and oxidization [7]. However, graphited or carbide layers remain as heat affected zone after removal process by nanosecond pulsed lasers [8, 9]. Ultrashort pulsed lasers make it possible to minimize the heat affected zone according to their short input time of energy, and precise shape creation can be performed [10]. These papers investigated shape creation process, but did not discuss the reduction of surface roughness, which is normally difficult in laser beam machining. Therefore, effects of shot number, average power and pulse repetition rate on surface roughness of monocrystalline diamond were experimentally investigated to perform small surface roughness by using a picosecond pulsed laser. In addition, crystalline characteristics of processed surface were evaluated after removal process.

## 2. Experimental procedures

Fig. 1 schematically shows the laser irradiation setup. A picosecond pulsed laser of 12.5 ps and 1064 nm wavelength was used as a laser source. A circular polarized laser beam of 0.8 mm in diameter was expanded by 4 times, and it was scanned on the workpice by a Galvan scanner with a telecentric type *f*θ lens of 100 mm in focal length. Laser irradiation experiments were carried out in air, and there is no assist and shielding gas at the processing point. Monocrystalline diamond of Ib type as the workpiece was pasted on a glass plate with a glue, and crystallographic orientation of top surface was (111). The axis of laser beam was perpendicular to the top surface of diamond.

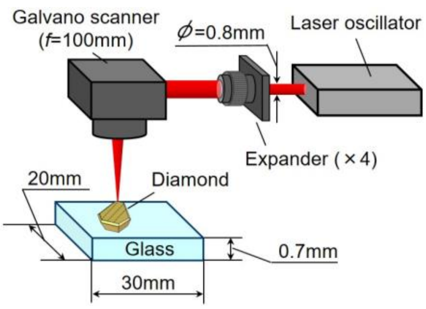


**Fig. 1**. Laser irradiation setup.

Main laser irradiation conditions are shown in Table 1. Pulse repetition rate was fixed at 200 kHz according to preliminary experiments to avoid excessive generation of graphite after laser irradiation. A spot diameter of laser beam on the workpiece surface was 25 μm, and shot number was defined as the case that the time of laser shot existed within the spot diameter of 25 μm during one laser scan. Only one laser scan was conducted in all experiments. Average power of laser beam was varied from 2.0 W to 4.0 W. Under one laser irradiation condition, 10 experiments were carried out, and the average of 10 measurements was recorded as the value of surface roughness.

**Table 1**
Main laser irradiation conditions

| | |
|---|---|
| Wavelength λ | 1064 nm |
| Polarization | Circular |
| Pulse duration $t_p$ | 12.5 ps |
| Spot diameter | 25 μm |
| Scan number | 1 scan |
| Pulse repetition rate $R_p$ | 200 kHz |
| Average power $P_a$ | 2.0 - 4.0 W |
| Shot number $N$ | 12.5 – 5000 shots |

## 3. Experimental results and discussion

### *3.1. Influence of shot number on surface appearance*

Influence of shot number on surface appearance was investigated. The shot number was varied by controlling the scanning speed of laser beam at the same pulse repetition rate of 200 kHz and spot diameter of 25 μm. Fig. 2 shows scanning electron microscope (SEM) images for various shot numbers at the same average power of 2.5 W. At 12.5 shots and 50 shots, slight surface modification could be observed on the processed surface, and grooves could be formed at more than 500 shots. The width of groove became wider with increasing the shot number, and periodic surface structures were created on the bottom area of groove in parallel direction of laser scanning line.

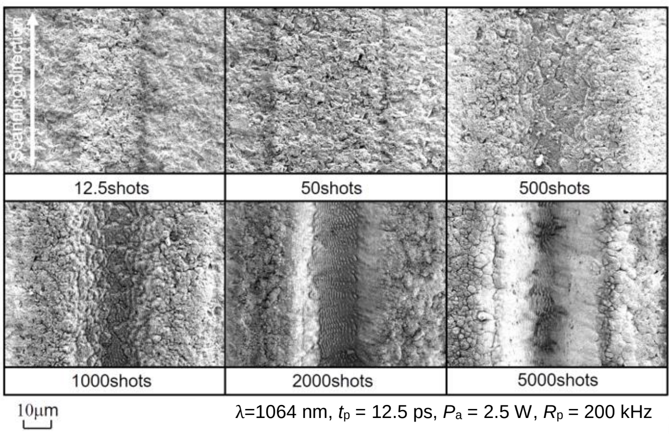


**Fig. 2**. SEM images of laser irradiated surface for various shot numbers at the same average power of 2.5 W and pulse repetition rate of 200k Hz.

In these laser irradiation experiments, the circular polarized laser beam was used. The generation of these periodic surface structures had been reported by using a liner polarized laser beam. In addition, the generating direction of periodic surface structures is normally in perpendicular direction to laser beam polarization [11, 12]. When the liner polarized laser beam was used by changing the optical setup, the generating direction of these periodic surface structures was still in parallel direction to laser scanning line regardless of polarization plane, and it appeared only after the generation of groove with a certain depth. Thus, these phenomena were caused by reflection of laser beam on the wall of groove, as reported by using nanosecond pulsed laser [7]. On the other hand, unique processing phenomenon could be observed only at 500 shots and 1000 shots.

Fig. 3 shows SEM images of unique surface processed at the shot number of 1000 shots and the average power of 3.0 W. The type of processed surface was mainly divided into two states. One is normal roughened surface as similar to the case obtained at other shot numbers, and the surface structure on the bottom of groove was similar to the wall of groove, as shown in Fig. 3 A. The other is almost flat surface at the bottom of groove, as shown in Fig. 3 B. In this paper, this area is described as new process in figures. Under the same laser irradiation condition, two processing types were mixed in one laser scanning line.

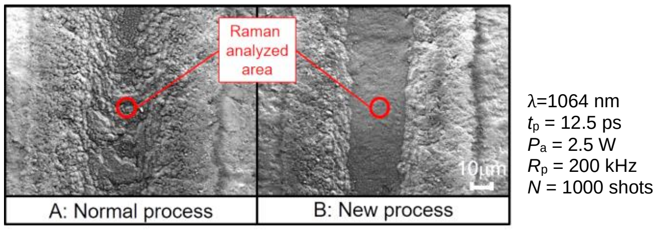


**Fig. 3**. SEM images of normal and new processed surfaces at shot number of 1000 shots and pulse repetition rate of 200 kHz.

Surface profiles of processed areas were measured by using a white light interferometric microscope, and surface roughness at the bottom surface of groove was evaluated as shown in Fig. 4. In normal process, the surface roughness increased after laser irradiation. On the other hand, new process could reduce the surface roughness by approximately 50 %. Its value is smaller than $R_a$=0.2 μm. Removal phenomena differ in normal and new processes, and the reduction of surface roughness as well as the shape creation of diamond can be expected by a series of the flat areas with new process.

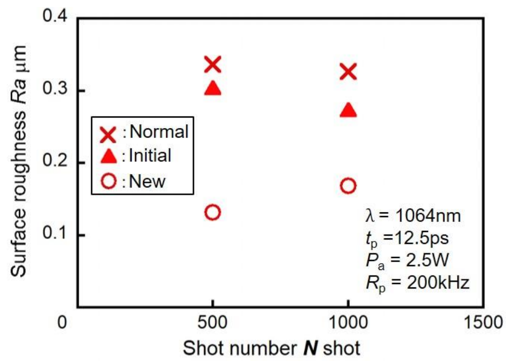


**Fig. 4**. Surface roughness of normal and new processed surface at shot number of 1000 shots and pulse repetition rate of 200 kHz.

In optical microscopic observation as shown in Fig. 5, colour of normal process area was recognized as black, which indicates that graphite or carbon remained on the processed surface after laser irradiation. On the other hand, new process area showed a little dark yellow colour, although laser beam irradiation was conducted in air. The reflection of light was quite different between normal and new processes, and it suggested the difference of composition on processed surface.

Red circle areas shown in Fig. 3 were analysed by Raman spectroscopy, and the measured spectra of normal and new process surfaces are shown in Fig. 6. In the case of normal process, both g-band around 1600 cm$^{-1}$ and d-band at 1333 cm$^{-1}$ appeared. Removal process of picosecond pulsed laser enabled good surface quality, but graphite and carbon would remained on the processed surface. This means that crystalline structure of diamond could not be kept in normal process. On the other hand, new process showed extremely sharp peak of diamond at 1333 cm$^{-1}$, although the pulse duration was the same as normal process. There was g-band peak around 1600 cm$^{-1}$, but its intensity was extremely lower than that at 1333 cm$^{-1}$. Judging from these results, the laser irradiation surface in new process could keep diamond crystalline structure mostly, although there was a little graphitization, which would be debris scatted from the processing point to the rear area. Thin graphited layer is easy to remove in post cleaning process.

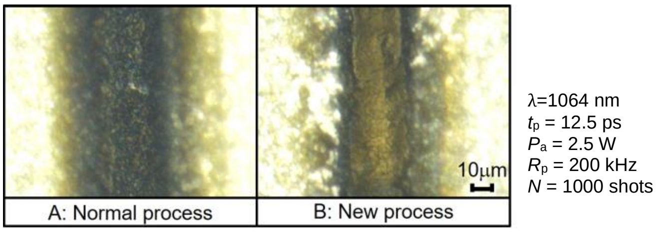


**Fig. 5**. Optical microphotographs of normal and new processed surfaces at shot number of 1000 shots and pulse repetition rate of 200 kHz.

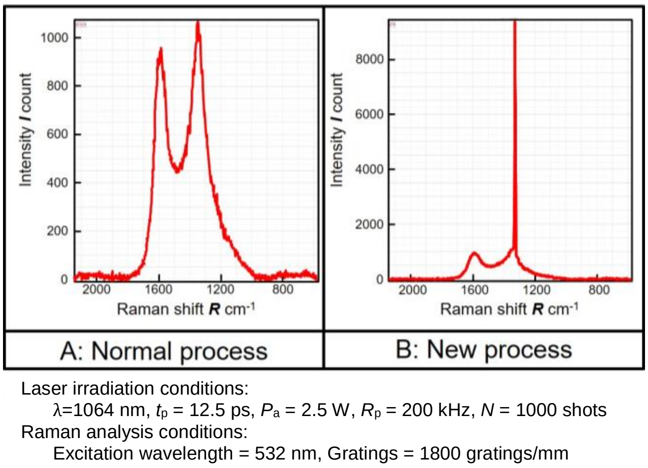


**Fig. 6**. Raman spectra of normal and new processed surfaces at shot number of 1000 shots and pulse repetition rate of 200 kHz.

*3.2. Effect of laser power on generation of smooth surface*

Both states of roughened and smooth surfaces appeared in one laser scanning line under the same laser irradiation condition, and the boundary area between two surface states is shown in Fig. 7. Smooth surface could be achieved in new process, but both surface sates were mixed. Next, generation ratio of the smooth surface was discussed by changing laser power, which relates the force acting on the surface of diamond.

Fig. 8 shows the generation ratio of smooth surface for various average powers at the same shot number of 1000 shots and the pulse repetition rate of 200 kHz. The generation ratio of smooth surface $GR_s$ was defined as that the length of smooth surface was divided by the whole length of process. The generation ratio of smooth surface increased with increasing the average power of laser beam, and it approaches approximately 80 % at more than 3.0 W average power. Further discussion may be needed to achieve much higher generation ratio of smooth surface, but this tendency means that a certain laser power, in other words, higher force to push the surface, is necessary to generate the smooth surface widely. In order to further understand the generation of smooth surface, absorption phenomena of laser energy is important, and surface states were compared before and after laser irradiation by observing the removal front of laser scanning.

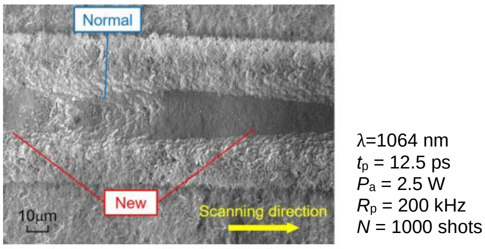


**Fig. 7**. SEM image of boundary region between normal and new processes at shot number of 1000 shots and pulse repetition rate of 200 kHz.

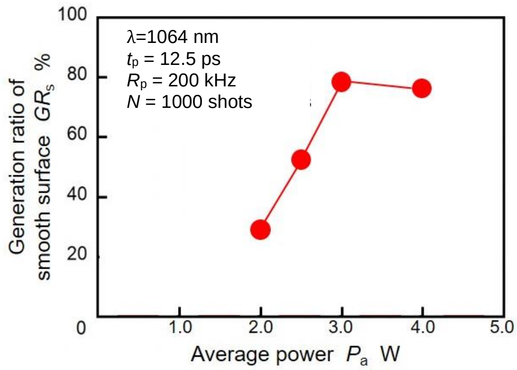


**Fig. 8**. Generation ratio of smooth surface for various average powers at shot number of 1000 shots and pulse repetition rate of 200 kHz.

*3.3. Mechanism to obtain smooth surface*

Laser irradiation was instantly stopped by changing the direction of laser beam axis with a reflection mirror, and removal front of laser scanning line was observed. Fig. 9 shows SEM images of removal front at the shot number of 1000 shots, the average power of 3.5 W and the pulse repetition rate of 200 kHz. In the top view, the bottom surface of groove was smooth, and stratiform structures could be observed at the front of removal area. The oblique view was taken, when the top surface of diamond was angled by 40 degrees. Although there was a little undulation on the smooth surface, the plane of smooth surface was almost parallel to the top surface of diamond. In addition, cracks were observed, and some of them propagated in parallel direction to the top surface of diamond. This means that the propagation direction of cracks was parallel to crystallographic orientation (111). It was explained that the (111) cleavage was found to be by far the most perfect and most abundant, because that plane has the minimum cleavage energy [13]. Thus, crystallographic orientation (111) is easy to be fractured compared to others. In addition, this cleavage phenomena was confirmed not only for other crystallographic orientations but also for polycrystalline diamond of nano-grains.

It is known that cracks propagated in the parallel direction of laser beam axis, when a laser beam was focused inside transparent materials [14]. On the other hand, it is reported that KABRA process could perform the separation of silicon carbide (SiC) wafer by the propagation of cracks in perpendicular direction of laser beam axis [15]. KABRA process generated the absorption layer inside SiC, cracks propagated in parallel plane to absorption layer, which was parallel to the top surface of wafer.

The propagation direction of cracks in the case of smooth surface was also perpendicular to laser beam axis, but the laser energy was mainly absorbed from the top surface of diamond. The absorbed area of laser energy was partly removed by ablation process, but the smooth and almost flat surface could be obtained in this experiment.

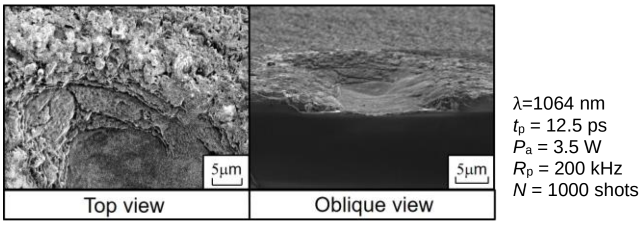


**Fig. 9**. SEM images of removal front in smooth surface state at shot number of 1000 shots and pulse repetition rate of 200 kHz.

In general, when surface of brittle material is forced with sharped tip of hard material, both median and lateral cracks are generated [16]. The direction of median and lateral cracks are parallel and perpendicular to the force direction of the sharped tip of hard material, respectively. When the top surface of brittle material is deformed by the sharped tip of hard material, elastic deformation area is generated below plastic deformation one. In this case, tensile stress concentrates due to plastic deformation, median crack is radially generated in perpendicular direction to the top surface of brittle material. After the force of the sharped tip of hard material is released, elastic deformation area tends to recover the original shape, while plastic deformation area cannot recover that. Then, lateral cracks propagate in parallel direction to the top surface of brittle material.

In this experiment, when the energy of laser beam is absorbed on the diamond, the diamond is removed by the combination of ablation and graphitization, as shown in Fig. 10. The density of graphite is approximately three fifth of diamond, and the volume increases as diamond changes into graphite. The layer of graphite is not completely divided from the layer of diamond, and diamond is gradually chaining into graphite. Thus, it is considered that the difference of stress would appears between graphited area and diamond crystalline area, and the composition obviously differs between graphite and diamond, which leads to the generation of cracks in parallel direction to the top surface of diamond. This direction is also crystal plane, and cleavage is far the most abundant in crystallographic orientation (111). Therefore, the lateral cracks propagated in parallel direction to crystallographic orientation (111) at the removal front of laser scanning line, and wide smooth and flat area could be formed by the connection of lateral cracks mentioned above. However, this cleavage is caused by complex phenomena, and further discussion is important to achieve stable cleavage process.

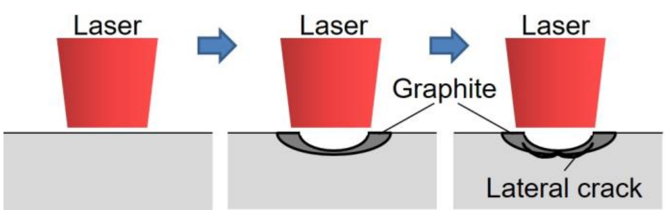


**Fig. 10**. Schematic illustration of lateral crack generation in micro machining of diamond by laser irradiation.

This newly developed process with smooth and flat surface can keep diamond structure, and both the reduction of surface roughness and the maintenance of diamond structure can be achieved. Thus, it is possible to reduce the time for creation process of shape and polishing process to final surface, and this process is effective in micro machining of diamond.

## 4. Conclusions

This paper reports removal phenomena of monocrystalline diamond to perform small surface roughness by using a picosecond pulsed laser. Both smooth and non-smooth areas are produced at specific shot number, and higher laser power than a particular value is necessary to obtain wide smooth surface. Cleavage phenomenon is observed on parallel plane to crystallographic orientation (111), and smooth surface can be obtained by stratiform removal. In addition, smooth surface can keep diamond crystalline structure mostly, although there remains a little graphitization. Further discussion is necessary to achieve much higher generation ratio of smooth surface, but this method can contribute to reduce the polishing process time in micro machining of diamond.

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