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Formation of smooth and flat area for monocrystalline diamond by ns pulsed laser

Yasuhiro Okamoto[a,*], Tubasa Okubo[a], Atsuya Kajitani[a], Akira Okada[a]

[a]*Okayama University, 3-1-1 Tsushima-naka, Kita-ku, Okayama 700-8530, Japan*

Abstract

The combination of ns pulsed laser and acid cleaning can achieve a smooth and flat surface below Ra=0.2 µm for monocrystalline diamond, when laser fluence is controlled around the threshold of removal. Although Gaussian mode is used, shiny and flat surface can be obtained in parallel direction to top surface of workpiece. Therefore, formation method of smooth and flat surface was experimentally investigated by repeating linear grooving, when ns pulsed laser of top-hat mode (1060 nm) was employed. However, subsequent linear grooving to previous one made it difficult to create flat surface with a constant depth, and two-step irradiation method was proposed. Non-removal areas were kept between processed lines in the first step, and the remained area between processed lines of the first step was removed in the second step. The two-step irradiation method was effective to achieve a wide flat-area with smooth surface, and it could improve the controllability of groove depth.

Keywords: micro machining; monocrystalline diamond; smooth surface; flat area; ns pulsed laser

1. Main text

Diamond has excellent properties such as high hardness, high conductivity and small coefficient of thermal expansion, as reported by Field et al., 1996. Diamond is widely used for cutting tools, and it is also expected as a semiconductor for high power devices, as introduced by Umezawa, 2018. However, conventional mechanical machining has difficulties to create the shape for diamond due its high hardness and brittleness. In the mechanical machining method, a long processing time is necessary with a large tool wear, but wide areas can be treated in one procedure.

On the other hand, laser beam machining can perform the shape creation of diamond efficiently without mechanical contact, and pulsed lasers with high peak power have been used to achieve the absorption of laser energy to diamond against its high transparency. In general, laser energy is absorbed at defects and/or surface in laser processing of diamond. Then, graphitized or carbonized material is removed by sublimation. However, in shaping process, it is difficult to achieve required surface roughness in many cases, and several polishing steps are needed to reduce the surface roughness below required level before finishing process. Polishing with diamond powder abrasive grains is used as a common method of finishing process, but these polishing steps are extremely time-consuming processes, which lead to the increase of production cost. Thus, in addition to create the shapes by laser beam machining, the reduction of surface roughness is very effective to reduce the cost and shorten the total processing time. Okamoto et al., 2019 reported that picosecond pulsed laser could form flat and smooth surface on monocrystalline diamond, but the processing widow was limited. If this process can be performed by normal nanosecond pulsed laser, further cost reduction and easy process setup can be expected.

In this study, the reduction method of surface roughness was investigated in shape creation process of diamond by nanosecond pulsed laser and influence of round Gaussian and square top-hat intensity distributions on removal characteristics was analyzed. Moreover, the formation method of flat area by repeating the linear micro-groove formation was discussed.

2. Experimental Procedures

A nanosecond pulsed laser of 200 ns pulse duration and 1060 nm wavelength was used in this experiment, and two optical setups were used. Main experimental conditions are shown in Table 1. One is the setup for round Gaussian beam, and 45 µm spot dimeter was obtained by focusing a laser beam of 10 mm diameter through a focusing lens of 100 mm focal length. The other is the setup for square top-hat beam. A laser beam of 10 mm diameter was focused into an optical fiber of 50 µm square core by using a focusing lens of 100 mm focal length, and 25 µm square spot was obtained by focusing a collimated beam through a focusing lens of 30 mm focal length. Both laser beams were focused at 20 µm above the surface of monocrystalline diamond.

The pulse repetition rate was fixed at 50 kHz, while laser fluence and shot number were varied. In line scanning experiment, shot number was defined as the number of laser pulse existing within the spots of 45 µm diameter and 25 µm square, respectively.

Monocrystalline diamond was normally classified into 4 types, as mentioned by Breeding, 2009, and Ib type, which is commonly employed in industrial applications, was used as a specimen. The monocrystalline diamond has crystallographic orientation, and the axis of laser beam was set in perpendicular direction to the (111) plane of monocrystalline diamond.

When one liner micro-grooving was carried out, monocrystalline diamond was processed in air without an assist gas. In multiple line scanning, compressed air of 90 L/min was supplied by a nozzle of 6.5 mm diameter. Shot number was defined as the case that the time of laser shot existed within the spot diameter, and the value of shot number was varied by controlling the scanning velocity at the fixed pulse repetition rate. The arithmetic average surface roughness was measured by a white interference microscope.

Table 1. Experimental conditions

Beam mode	Round Gaussian	Square top-hat
Wavelength	1060 nm	
Polarization	Random	
Pulse duration	200 ns	
Pulse repetition rate	50 kHz	
Collimation les	-	*f* 100 mm
Focusing lens	*f* 100 mm	*f* 30 mm
Spot diameter	45 µm	25 µm

3. Experimental Results and Discussion

3.1. Round Gaussian beam

Firstly, a round Gaussian beam was used for the formation of line micro-groove on the surface of monocrystalline diamond. Figure 1 shows optical microscope and SEM images of micro-groove processed by the round Gaussian beam, before and after acid cleaning, when line scan was conducted at 3.1 J/cm^2 fluence and 100 shot number. A black area could be observed on the surface around the scanning line just after micro-grooving process, and this black area could be identified as graphite according to the evaluation results of Raman spectroscopy analysis. The graphite deposited on the surface could be removed by acid cleaning. From the optical microscope image after acid cleaning, shiny areas could be observed at the bottom of micro-groove, and the Raman spectroscopy results showed to keep the diamond crystal structure. As shown in SEM image after acid cleaning, it is seen that the surface roughness decreased at the bottom of micro-groove compared with that of top surface. In addition, very flat surface could be obtained at bottom surface of micro-groove in perpendicular plane to the beam axis, although the round Gaussian beam was used.

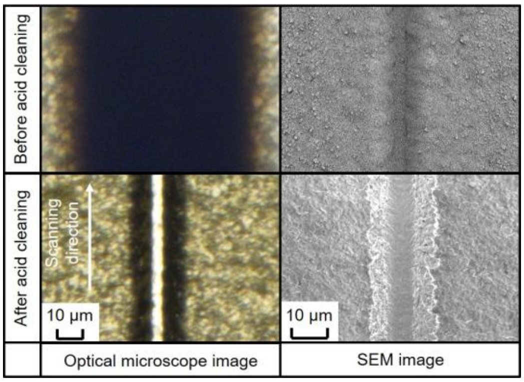


Fig. 1. Optical microscope and SEM images of micro-groove before and after acid cleaning at 3.1 J/cm^2 fluence and 100 shot number

Figure 2 shows the measurement results of surface roughness at the bottom plane of micro-groove for various fluences after acid cleaning, when the round Gaussian beam was scanned at 100 shot number. The surface roughness at the bottom plane of micro-groove decreased with decreasing the laser fluence, and the minimum surface roughness less than 0.1 µm could be obtained around the processing threshold of removal.

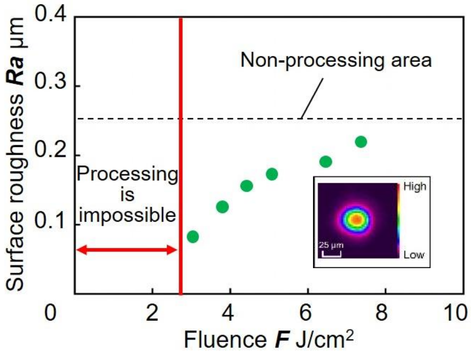


Fig. 2. Surface roughness at bottom plane of micro-groove created by round Gaussian beam at 100 shot number

3.2. Square top-hat

In order to increase the bottom width of micro-groove, a square top-hat beam was used instead of the round Gaussian beam. Figure 3 shows the measurement results of surface roughness at the bottom plane of micro-groove for various fluences after acid cleaning, when the square top-hat beam was scanned at 100 shot number. The surface roughness became almost half of initial surface roughness, and the reduction of surface roughness at the bottom plane of micro-groove could performed around processing threshold of removal, as similar to that by the round Gaussian beam. The square top-hat beam requires a large laser fluence to obtain the flat and smooth surface, but its processing window is wider than that by the round Gaussian beam.

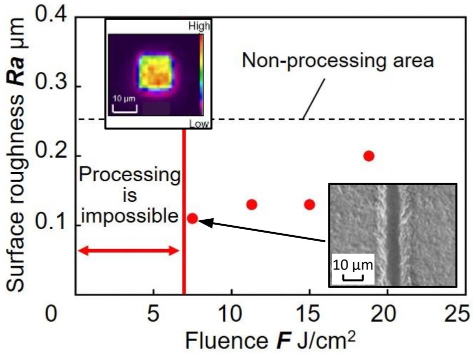
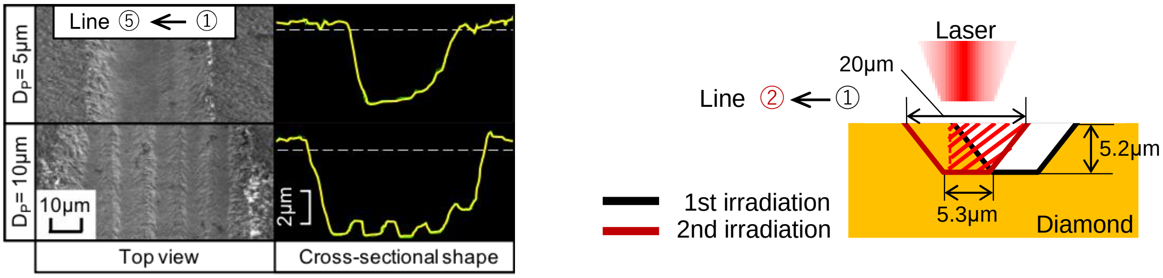


Fig. 3. Surface roughness at bottom plane of micro-groove created by square top-hat beam

3.3. Formation of wide flat area with smooth surface

To create the wide flat area with smooth surface by using the square top-hat beam, the line micro-grooving was repeated by 5 times at the pitch interval of 5 µm and 10 µm, as shown in Fig. 4. Here, processing lines were formed from the right to the left side under the condition of 7.5 J/cm^2 pulse energy and 100 shot number, and compressed air was used as an assist gas to remove the debris. Unfortunately, as shown in SEM images of top views and the cross-sectional shapes of Fig. 4 (a), the depth of micro-groove increased in the second and subsequent lines compared with that of first line, and convexities were remained between processed lines at a pitch interval of 10 µm. Figure 4 (b) schematically shows the situation of process at the second line by the pitch interval of 5 µm, after the formation of first line. The number of lines increased from the right to the left



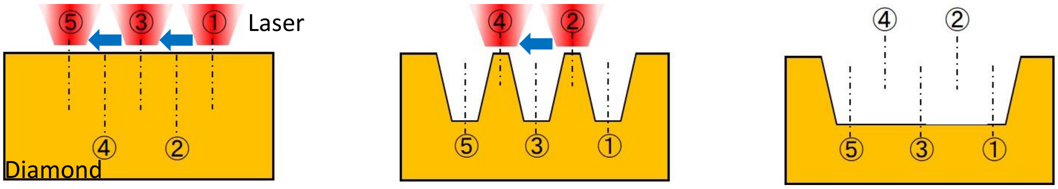
(a) Experimental results

(b) Situation of process at second line

Fig. 4. Creation of wide area by normal repetition of line micro-grooving under 7.5 J/cm^2 fluence and 100 shot number, (a) SEM images and cross-sectional shapes of grooves by pitch of 5 µm and 10 µm; (b) Situation of process at second line by pitch of 5 µm

side. The red hatching part is the removal area in the second line, when it is assumed that the same area as the first line is removed in the second one. As shown in the figure, the assumed area of removal in the second line partly overlaps with that in the first one, and the height of material's surface in the second line is different from that in the first one. Thus, it is considered that the depth of micro-groove increased with increasing the number of lines. Judging from these results, it is difficult to form wide flat area with smooth surface by continuous repetition of linear micro-grooves. Next, two-step irradiation method was proposed to achieve the wide flat area with smooth surface.

Figure 5 shows the schematic illustration of two-step irradiation method, and five lines are created from the right to the left side. As shown in Fig. 5 (a), line micro-grooving is carried out at the lines of numbers 1, 3 and 5 in the first step. As shown in Fig. 5 (b), non-removal areas with initial height surface are kept between processed lines of the first step, and the remained area between processed lines of the first step is removed by the lines of number 2 and 4 in the second step. Then, it can be expected that the wide flat area is created at the bottom surface of processed area, as shown in Fig. 5 (c).



(a) 1st step (b) 2nd step (c) After 2nd step

Fig. 5. Schematic illustration of two-step irradiation method procedure by 5 lines, (a) Irradiation lines in 1st step; (b) Irradiation line in 2nd step, (c) Shape of groove by 5 lines after 2nd step

Figure 6 shows experimental results of two-step irradiation method. The first step conditions are 7.5 J/cm^2 laser fluence and 25 shot number, and 6.0 Jcm^2 and 25 shot number were selected as the second step conditions. As shown in the top view of SEM photograph and cross-sectional shape, the first step creates three lines, and non-removal areas with initial height surface exist between lines of the first step. In the second step, remained areas between processed lines in the first step is removed in the second step, and continuous flat and smooth surface area could be formed with very small step less than 50 nm. Two-step irradiation method with the square top-hat beam can improve the controllability of micro-groove depth, which achieve a wide area of continuously flat and smooth surface.

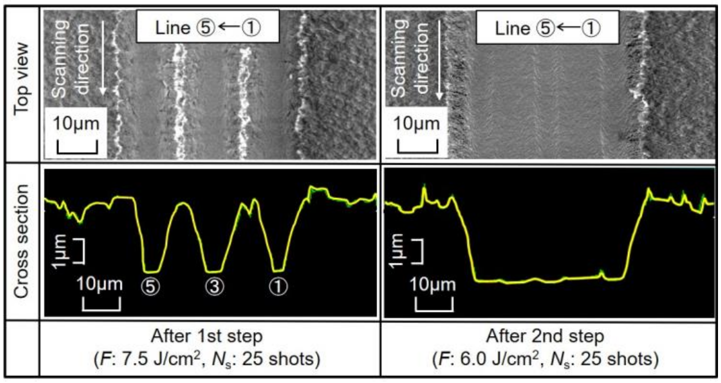


Fig. 6. SEM images and cross sections of processed shapes by two-step irradiation method at pitch interval of 16μm

4. Conclusions

The reduction method of surface roughness was investigated in shape creation process of diamond by nanosecond pulsed laser of round Gaussian and square top-hat beams. In addition, the formation method of flat area by repeating the linear micro-groove formation was discussed. Main conclusions obtained in this study are as follows:

(1) The surface roughness at the bottom surface of micro-groove can be reduced stably by a combination of nanosecond pulsed laser irradiation and acid cleaning.
(2) Square top-hat beam can create a micro-groove at wider processing window than round Gaussian beam.
(3) Two-step irradiation method, in which the height of second removal areas should be similar to the depth of first removal ones, can improve the controllability of micro-groove depth, and this method is useful to achieve a wide flat area with smooth surface by repeating the formation of linear micro-groove.

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