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Cutting of monocrystalline diamond tools using short pulse UV laser

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Diamond tools are indispensable for the precision machining of hard and brittle materials, whose industrial demand has been increasing in recent years. Generally, diamond tools are formed by skilled workers lapping with fine diamond abrasive grains. In this case, the lapping process is time consuming and the removed diamond chips cannot be used. High-purity IIa type diamonds transmit laser light and cannot be laser processed, whereas Ib type diamonds that contain a small number of impurities can be laser processed. In this study, Ib diamond was cut using a short wavelength UV laser, and the surface texture and processing efficiency of the processed surface were evaluated. We successfully achieved high quality and high efficiency cutting by the shift plunge cutting method using the newly developed UV laser. Moreover, this method allows the use of laser-cut diamond fragments as a tool.

NOMENCLATURE

d_0 = diameter of laser spot
f = focus length of lens
λ = wavelength
D = laser diameter
Z_R = Rayleigh length
Z = beam diameter

1. Introduction

Diamond tools have the highest hardness among all materials, high thermal conductivity, wear resistance, and resistance to the formation of compositional cutting edges. However, their hardness makes machining difficult.

In recent years, laser processing, which is high-speed and allows non-contact machining, has been used to process diamonds. However, laser processing does not provide sufficient surface roughness owing to the carbonization of diamond caused by the high temperature of irradiation, and a long-time duration is required for finish polishing. This results in the high cost of diamond tools and a long machining time.

Therefore, it is necessary to reduce the processing cost by shortening the time required for the final polishing by performing high-quality laser cutting. In this study, a nanosecond pulsed UV laser was used to cut monocrystalline synthetic diamond to achieve efficient laser slicing conditions.

2. Experimental Device

Table 1 Property of monocrystalline diamond

Type of material	Monocrystalline Synthetic Diamond (Ib, PD1140, Sumi crystal)
Density	3.515×10^3/m^3 (25 ℃)
Lattice constant	3.567 Å (25 ℃)
Young's modulus	1050 GPa
Coefficient of thermal expansion	1.5×10^{-6}/K (78 ℃), 3.5×10^{-6}/K (400 ℃)
Relative permittivity	5.7 (1 MHz)
Refractive index	2.41 (λ=656.3 nm)
Manufacturer	Sumitomo Electric Industries, Ltd.

A monocrystalline synthetic diamond (Type Ib), as presented in Table 1, is used for the laser slicing experiment. As shown in Fig. 1, the transparency of this diamond drops sharply for light with a wavelength of 400 nm or less. This indicates that commonly used YAG or green laser wavelengths have more than 60% transmittance and are unsuitable for cutting Ib diamonds. Therefore, for this laser-cutting experiment, a UV laser with a wavelength of 355 nm was used.

Fig. 2 shows a schematic of the nanosecond laser oscillator used in this study, and Table 2 lists the specifications of the laser oscillation system used. The optics of the laser processing system consist of a reflective mirror, beam expander, and focusing lens. A Nd:YVO laser with a pulse width of 13 ns, oscillation frequency of 30 kHz, and wavelength of 355 nm were used to irradiate the workpiece to achieve a minimum spot diameter of 6.7 μm for processing. The focal point was adjusted, and the laser was scanned using an XYZ stage (ALS(ALZ)-906-E1P (Chuo Precision Industrial).

An optical microscope MM-400 was used for observation and measurement of the test diamond.

3. Experimental Methods and Results

In this study, four types of experiments were carried out: (1) the effect of the laser oscillation frequency; (2) the effect of the laser scanning speed; and (3) the effect of the focus point movement. The authors evaluated the machined groove depth and heat effect around the groove.

3.1 Effect of oscillation frequency on groove depth

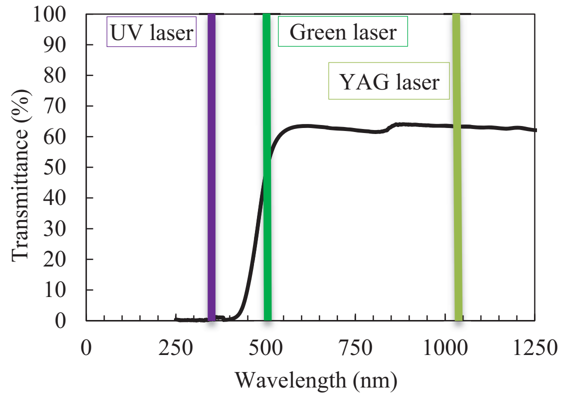
The diamond was sliced at a laser oscillation frequency of 30–100 kHz and a scanning speed of 1 mm/s. The laser was focused on the diamond surface and scanned the diamond in one direction. The processed surface was then refocused, and the diamond was scanned in the opposite direction.

As shown in Fig. 3, the machined groove became shallower as the oscillation frequency increased. As the output of this laser decreased and the oscillation frequency increased, the groove depth reached its maximum value at 30 kHz. Therefore, in this study, a cutting experiment was performed with an oscillation frequency of 30 kHz as the basic condition.

3.2 Effect of scanning speed on groove depth

Fig. 4 shows the groove depths when the scanning speed is varied from 0.2 to 16 mm/s under the condition that the oscillation frequency is 30 kHz and the number of diamond scans is one. As the scanning speed increased, the depth of the machined groove decreased. The red curve in the figure shows the removed volume per unit width and time. Based on this result, a scanning speed of 16 mm/s was selected as the condition for a faster slicing time.

3.3 Effect of focus point change on groove depth



When cutting with a laser in multiple steps, there is a problem that

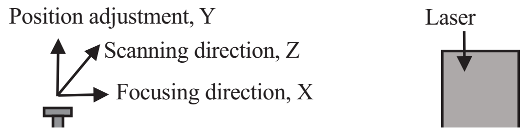


Fig. 1 Transmission characteristics of monocrystalline diamond, Type Ib

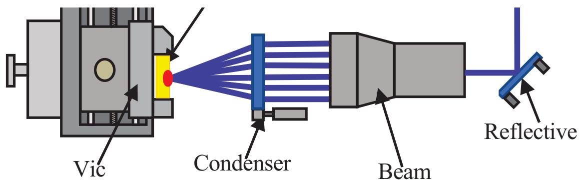


Fig. 2 Schematic diagram of nanosecond laser processing system

Table 2 Specification of laser oscillator

Unit name	AONano 355 5-30-V (Advanced Optowave)
Laser source	Nd:YVO
Wavelength	355 nm
Average power	～5.7 W
Pulse width	13～70 ns
Repetition rate	30～300 kHz
Beam roundness	90% <

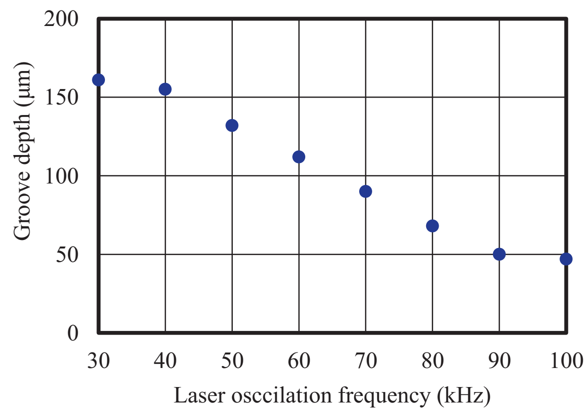


Fig. 3 Effect of laser oscillation frequency on groove depth (Scanning speed: 1 mm/s)

the focal position shifts when the processing depth changes. Therefore, the focal point must be changed for each pass. When cutting with a laser in several cuts, there is a problem that the focus point shifts as the processing depth changes. Therefore, it was necessary to change the focus point during this process.

Fig. 5 shows that the maximum cutting depth is reached when cutting the diamond while moving the laser focal position at a depth of 8 µm per pass.

3.4 Laser slicing experiment

As shown in Fig. 6, when a laser with a Gaussian distribution of diameter D and wavelength λ is focused by a lens with focal length f, the spot diameter d_0 at the focal position is expressed by (1). The Rayleigh length Z_R is given by (2). The beam diameter at position Z away from the focus position is given by (3).

Thus, in the cutting method in which the laser cuts once and then scans, the laser beam interferes with the edge of the processed groove. This results in less power at the focal point, less light output, and more difficult-to-cut thick diamonds.

$$d_0 = \frac{4f\lambda}{\pi D} \quad (1)$$

$$Z_R = \frac{4\lambda}{\pi}\left(\frac{f}{D}\right)^2 \quad (2)$$

$$d = d_0\sqrt{1 + \left(\frac{Z}{Z_R}\right)^2} \quad (3)$$

Therefore, after moving the focal point in the laser irradiation direction (-X direction) to make a through-hole, the irradiation position is shifted in the Y direction to repeat the process of making a through-hole. Through this process, we successfully cut diamonds with a thickness of 1 mm or more.

As shown in Fig. 7, the table is scanned in the Y-axis direction to irradiate the diamond with a laser beam (1) → (2), and the focal position a is moved in the X-axis direction to perform a plunge cut (3). Next, it scans in the Y-direction, and when the laser beam leaves the diamond, it cuts by moving the focal position in the X-direction. Diamond cutting was attempted by repeating traverse laser cutting. Here, this processing method is referred to as "traverse laser cutting".

Figure 8 shows a microscopic view (MM-400 Nikon) of the machined diamond surface under transverse laser cutting. The diamond could not penetrate, and the processed groove was curved.

Hidai et al. used a high-speed camera to photograph a phenomenon in which soda-lime glass was cut by a CO_2 laser with a wavelength of 10.59 µm, and the crack did not follow the laser irradiation path, curved toward the free edge, and then progressed almost parallel to the free edge[1]. This was attributed to the propagation of cracks in the hard and brittle materials. A similar reason can be considered for diamond cutting; however, a more detailed study is required.

As shown in Fig. 9, the laser focus point approaches the diamond at

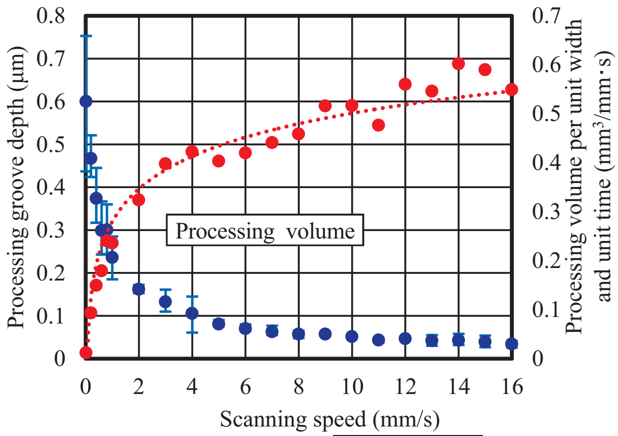


Fig. 4 Effect of scanning speed on groove depth
(Oscillation frequency: 30 kHz, 1 pass scanning)

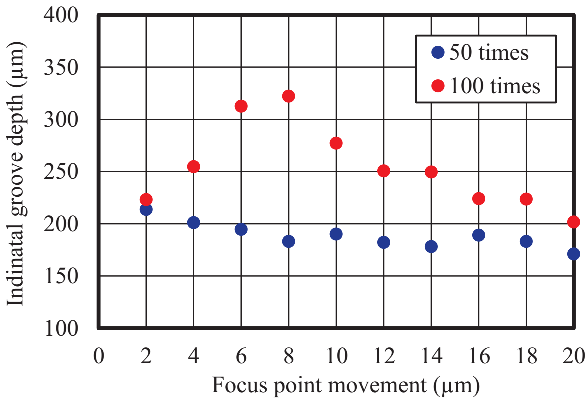


Fig. 5 Effect of focus point change on groove depth (Oscillation frequency: 30 kHz, Scanning speed: 16 mm/s)

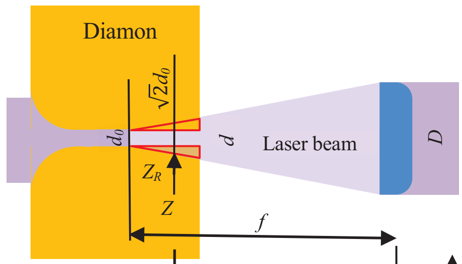


Fig. 6 Schematic of a ray model of the

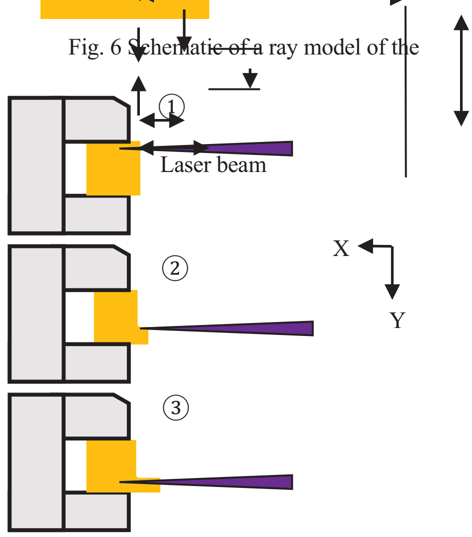


Fig. 7 Focal point change after laser scanning

2 μm or 3 μm steps with an oscillation frequency of 30 kHz. After making the diamond holes, the laser focus point was moved by 1 mm in the Y direction at a scanning speed of 16 mm/s. This process was repeated to slice the diamond.

As shown in Fig. 10, the surface integrity of the 2 μm focus steps is better than that of the 3 μm focus steps.

Conclusion

Laser slicing experiments were conducted on type IIb-synthesized monocrystalline diamond using a nanosecond-pulsed UV laser with a frequency of 30 kHz, scanning speed of 16 mm/s, and the following conclusions were obtained.

1) Scanning under 1 pass oscillation, a groove with an average depth of 0.012 mm was formed.
2) By changing the focal point every 8 μm/pass, a groove with a depth of 32 mm was obtained under 50 scan cycles.
3) The traverse laser cutting method could not cut 1.1 mm square diamonds because the processed groove was curved.
4) Complete slicing could be performed by scanning the focal direction in addition to the scanning direction.
5) The surface integrity of smaller focus steps was better than that of larger focus steps.

Acknowledgement

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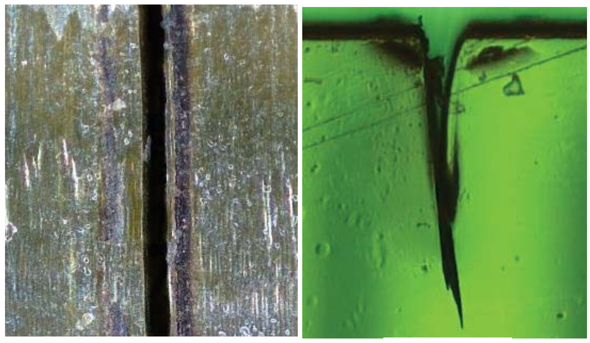


a) Irradiation surface b) Cut surface
Fig. 8 Microscopic photo after laser cutting

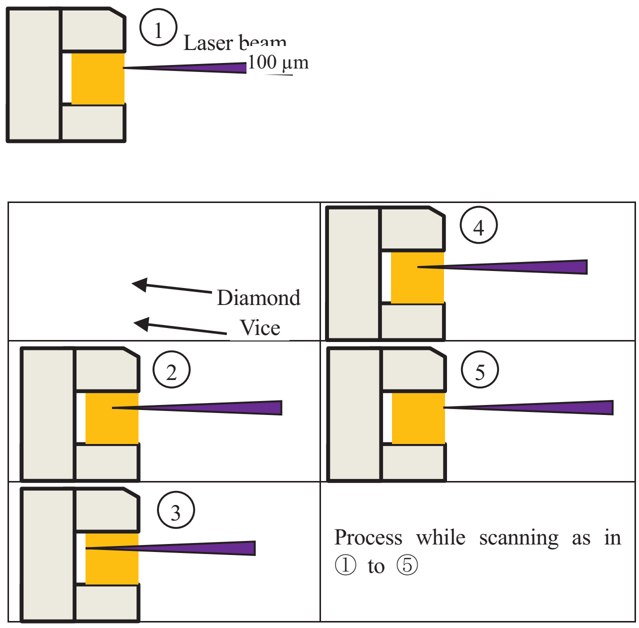


Fig. 9 Laser slicing process

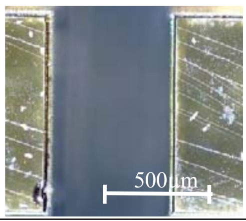
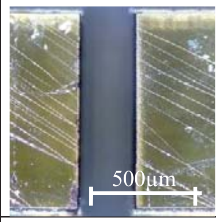
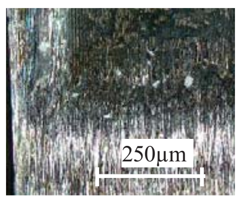
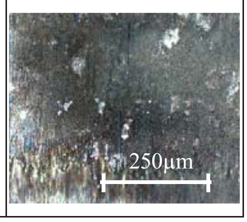
	Focal direction movement 3 μm steps	Focal direction movement 2 μm steps
Irradiation surface		
Cut surface		

Fig. 10 Microscopic photo of laser sliced surface
(Synthesized monocrystalline diamond, type Ib)