Development of Microfabrication Technology using DUV Laser

YUJI IMAMIYA[*1] **SATORU AKAMA**[*1]

YOSHIHITO FUJITA[*2] **HARUHIKO NIITANI**[*3]

Laser machining technology has advanced significantly in recent years and has been applied in various different fields for industrial use due to its convenience and the great variety of applicable materials. In laser micromachining represented by drilling, high-quality and high-precision machining is possible by utilizing a short-pulse laser. However, a higher level of precision is desired. Mitsubishi Heavy Industries Machine Tool Co., Ltd. has developed an optical system utilizing a Deep Ultraviolet (DUV) laser in which further improvement is expected in the machining resolution, and has successfully identified the machining characteristics of individual materials. Furthermore, a drilling test was conducted with a laser micromachining unit equipped with a newly-developed optical system, which, as a result, achieved ultrafine drilling to make a hole of a minimum of 10μm in diameter and an aspect ratio of 10.

1. Introduction

As electronic devices have become increasingly smaller in recent years, various components including electronic parts and printed circuit boards that used in such devices have been miniaturized and have become increasingly sophisticated. Consequently, there is growing demand for further miniaturization and increased quality of ultraprecision machining including drilling. As a means to satisfy such demand, a machining method that utilizes a short-pulse, short-wavelength laser has attracted attention. Utilizing a short-pulse laser such as a picosecond pulse laser enables ablation with no thermal effects, achieving high-precision machining with superior quality. In addition, using a short-wavelength laser can make the condensing spot diameter of a laser beam smaller, which enables finer machining. Currently, as shown in **Figure 1**, popular short-pulse lasers for micromachining include the Nd:YAG laser (Wavelength: 1064nm), followed by the green laser by the second harmonic generation of the Nd: YAG laser (Wavelength: 532nm) and the UV laser by the third harmonic generation of the Nd:YAG laser (Wavelength: 355nm). On the other hand, the Deep Ultraviolet (DUV) laser by the fourth harmonic generation (Wavelength: 266nm) has not been widely used due to its difficulty in handling, having made very little actual achievement as a micromachining system(1). However, the short wavelength can make the focused laser spot diameter small at the irradiation point, from which finer hole-drilling can be expected. In addition, the DUV laser has high absorbance through various materials and high light energy, which is expected to be applicable to materials that have been difficult to machine using conventional methods.

Mitsubishi Heavy Industries Machine Tool Co., Ltd. (MAT) has already brought the “ABLASER” Laser Micromachining System equipped with a picosecond green laser to market(2). Subsequently, the company developed an optical system and machining technology utilizing a picosecond DUV laser for the purpose of achieving finer hole-drilling with higher quality. This paper will clarify the basic machining characteristics of picosecond DUV lasers, and will introduce actual ultrafine drilling performed by ABLASER utilizing the DUV laser.

---

*1 Advanced Manufacturing System Development Center, Mitsubishi Heavy Industries Machine Tool Co., Ltd.
*2 Chief Staff Manager, Advanced Manufacturing System Development Center, Mitsubishi Heavy Industries Machine Tool Co., Ltd.
*3 General Manager, Advanced Manufacturing System Development Center, Mitsubishi Heavy Industries Machine Tool Co., Ltd.

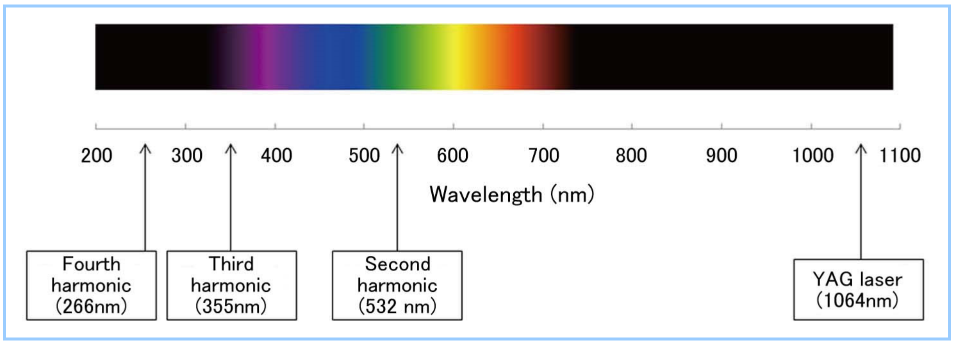

Figure 1 Various types of laser beams depending on the wavelength

2. Structure of DUV laser optical system and its machining characteristics

2.1 Optical laser focusing system for DUV laser

In laser micromachining, a laser beam is focused and irradiated on the surface of the target workpiece from which the debris produced by machining is removed by the light energy. At the time of irradiation, when the focused laser spot diameter is smaller, the area from which the debris needs to be removed also gets smaller, which increases the quality of micromachining. In order to achieve a smaller focused laser spot diameter, there are multiple means, such as utilizing a short-wavelength laser, enlarging the spot diameter before focusing and shortening the focal length. However, when the wavelength of the laser light reaches the ultraviolet range, the laser's absorbance through glass materials increases. Therefore, it is necessary to ease the strain on optical element materials such as the lens. In other methods, the convergence angle is large, which is likely to cause a gap in size of the hole between its entrance and exit and to reduce the focal depth, limiting the shape of the hole created by drilling. The newly-developed optical laser focusing system adopts the DUV laser, which offers a small diameter of the condensed light. Therefore, the durability of the lens was ensured by testing the durability against the DUV laser beam of the glass used for the optical element beforehand, while selecting the optimal glass material and setting an appropriate laser irradiation intensity. Furthermore, by optimizing the focal length and lens form, the convergence angle is minimized and a long focal depth is achieved, while the focused laser spot diameter remains very small.

2.2 Assessment of focused laser spot diameter of DUV laser

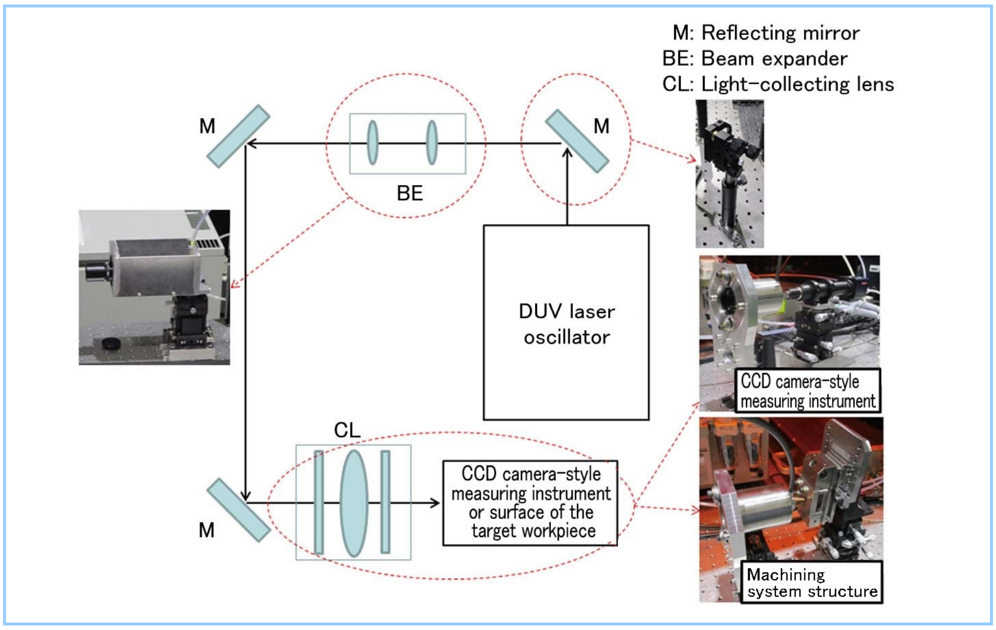

Figure 2 Structure of the focused laser spot diameter measuring system of DUV laser

Based on the study described in 2.1 above, a prototype optical laser focusing system for DUV laser was created in order to confirm the expected level of micromachining by measuring the focused laser spot diameter and energy distribution. **Figure 2** shows the structure of the spot diameter measuring system. The beam emitted from a DUV laser oscillator is transmitted through the total reflection mirror which simulates the optical transmission path of a laser machining device to be installed and condensed through a focusing lens.

Figure 3 shows the energy distribution at the focal point measured by a CCD camera-style measuring instrument. The energy distribution is mostly consistent with the expected Gaussian distribution, which is ideal, and the measured spot diameter was 5.7μm. On the other hand, the designed diameter thereof calculated in accordance with the theoretical formula is 5.5μm, which is mostly consistent with the measured value. Compared with the spot diameter by ABLASER utilizing MAT's conventional green laser, the diameter of a DUV laser beam is about a half of that of the green laser, from which finer hole-drilling can be anticipated. In addition, the ellipticity at the focal point is 0.998, which confirms that hole-drilling with high accuracy can be expected.

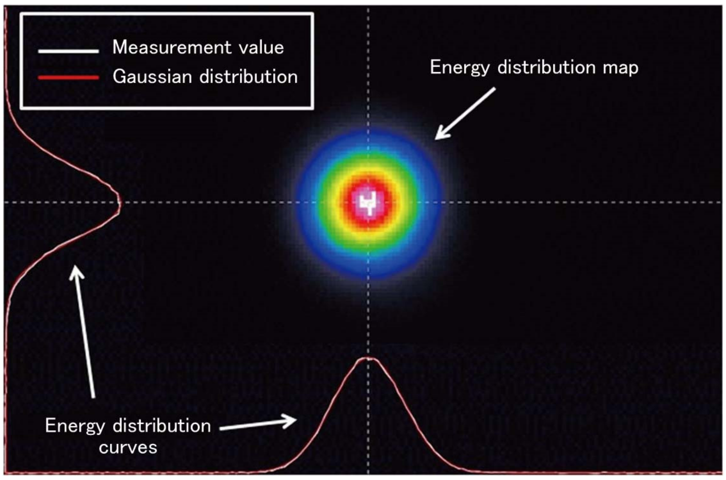

Figure 3 Energy distribution at the focal point
The focused DUV laser spot diameter is 5.7μm and the energy distribution results in ideal curve in agreement with Gaussian distribution.

2.3 Examination of fabrication rate of DUV laser beam with various materials

Fabrication rates of a DUV laser beam and green laser beam (wavelength: 515 nm) with various different materials are obtained in order to compare and evaluate their characteristics. In an optical system structure similar to the focused spot diameter measuring system, individual materials are placed at the focal position (Figure 2). The materials listed in **Table 1** were individually irradiated with a focused DUV or green laser beam by 1 pulse only in order to measure the depth of the hole made by drilling with a 3D laser scanning confocal microscope (VK-X150/160) manufactured by Keyence corporation. As the cross section of the hole after drilling is cratered, the measurement was carried out in terms of the maximum depth at the center of the hole. Fabrication rates for individual materials were obtained by conducting machining and measurement with different levels of pulse energy.

Table 1 Materials used for 1-pulse irradiation test with DUV and green laser beam

Metal	Stainless steel
Semiconductor	Single-crystal silicon carbide wafer
Resin	Polyethylene terephthalate
Glass	Borosilicate glass

The measurement results are shown in **Figure 4**. The vertical axis of the chart indicates the fabrication depth, while the horizontal axis represents the energy intensity of the irradiated laser beam. As shown in Figure 3, the energy distribution is uneven within the irradiation range. Therefore, the intensity is calculated using an energy value near the center.

Fabrication rates were compared between the DUV laser beam and the green laser beam where a noticeable difference was confirmed in every material. **Figure 5** shows fabrication marks and cross-sectional views of holes produced by both lasers. A single-crystal silicon carbide wafer (SiC), a compound semiconductive material, has a high degree of hardness and chemical stability where precision machining and fabrication based on chemical actions are extremely difficult.

Therefore, laser-based precision machining is highly expected to be capable of handling this material. However, due to the large bandgap, a short-wavelength laser beam which has a higher light energy than other types of laser beams is considered suitable for machining. In this experiment result, the fabrication rates of the green laser beam were fairly low and materials melted within the laser irradiation range. On the other hand, the DUV laser beam, which has a high light energy, achieved relatively high fabrication rates and the cross-sections of the fabrication marks were similar to the Gaussian distribution. Therefore, precise machining can be expected in ultrafine hole-drilling as well. The DUV laser beam successfully formed clear fabrication marks on borosilicate glass. The green laser beam mostly penetrates materials, which makes the fabrication itself extremely hard, and the fabrication rates obtained are very low. With the DUV laser, fabrication marks were confirmed to have very little melting on the surface of the workpiece where reattachment of debris removed was hardly observed. Accordingly, it is assumed that ideal ablation phenomena are induced, from which high-quality ultrafine hole-drilling can be expected. The DUV laser beam achieved higher fabrication rates for stainless steel than the green laser beam, demonstrating its superiority. Further, the green laser beam created bubbles in the fabrication marks on polyethylene terephthalate, a high-polymer material, which indicated melting of the materials. On the contrary, an ablation activity with less thermal effects and sufficient fabrication rates were confirmed with the DUV laser beam.

Accordingly, the superiority of the DUV laser to the green laser beam was verified with multiple materials, and it is also possible to estimate the optimum pulse output in order to obtain the fabrication depth required for individual materials. Thus, improved machining quality and optimized performance are possible.

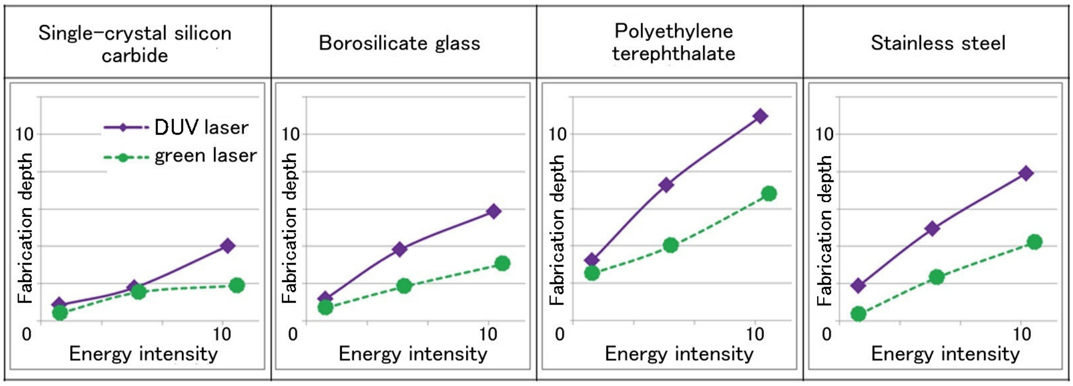

Figure 4 Fabrication depth of individual materials corresponding to the energy intensity of DUV and green laser

Normalized values are utilized for the vertical and horizontal axes. All charts utilize a unified scale.

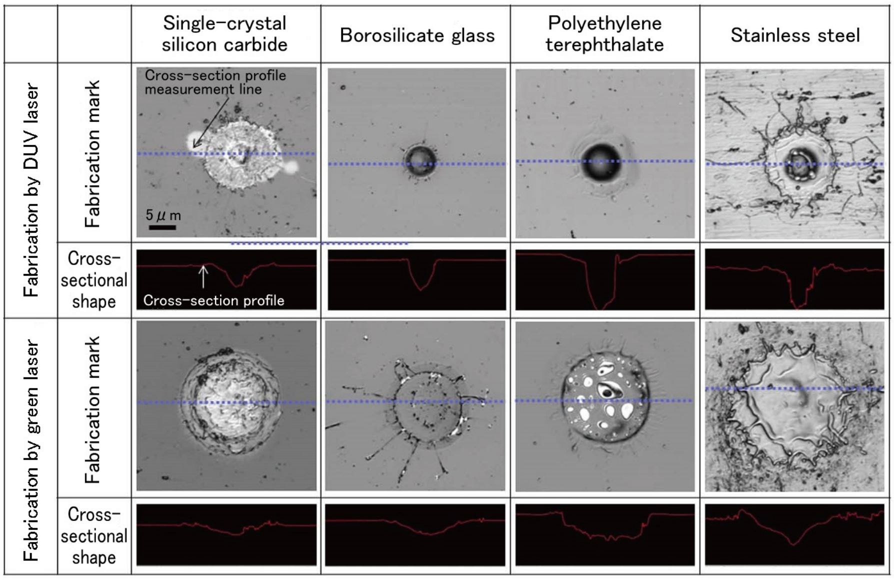

Figure 5 Images of fabrication marks by 1-pulse irradiation on individual materials and their cross-sectional views

A unified scale is utilized for all images and cross-sections.

3. Actual machining conducted with ABLASER utilizing DUV laser

A drilling test was conducted utilizing an "ABLASER" laser micromachining system equipped with a DUV laser optical system. ABLASER has already been offered on the market by MAT. In order to achieve high-quality hole-drilling, ABLASER adopts the helical drilling method in which the path of the laser beam can be rotated and adjusted with high accuracy as shown in **Figure 6**. In addition, an optical head, one of our unique developments, allows the control of the incidence angle as well as the rotation diameter of the laser beam as shown in **Figure 7**, which can achieve any hole diameter and cross-sectional shape.

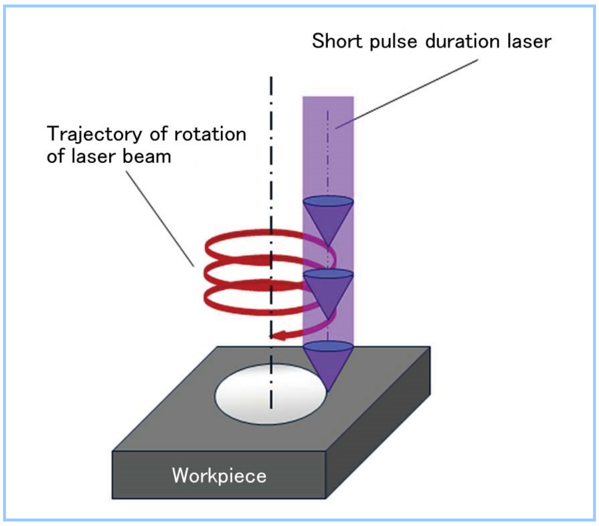

Figure 6 Helical drilling method
The helical drilling is carried out while rotating the laser beam at a high speed with an arbitrarily-adjusted rotation diameter and irradiating with a pulse laser.

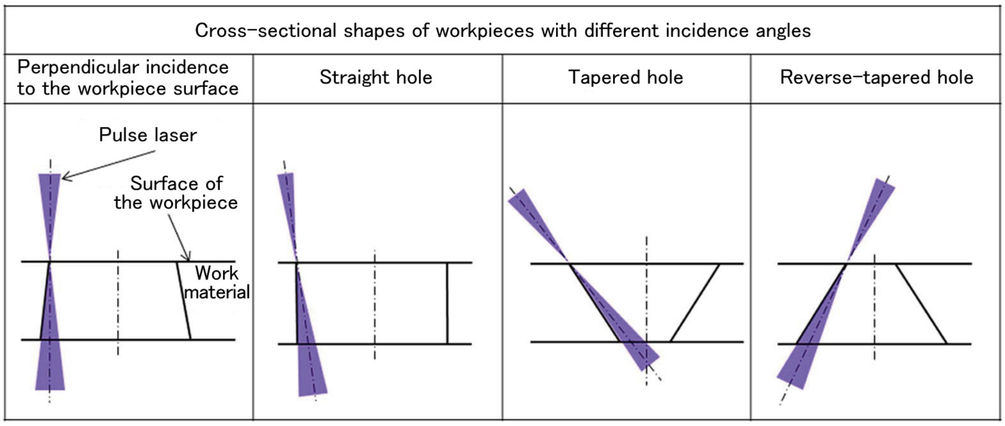

Figure 7 Control of the laser incidence angle by ABLASER
Drilling can achieve arbitrary cross-sections such as a straight hole, a tapered hole and a reverse-tapered hole by controlling the incidence angle of a laser beam.

According to the machining characteristics obtained from the 1-pulse irradiation test described above, laser irradiation conditions were determined, based on which hole-drilling was performed on stainless steel and a single-crystal SiC wafer. A hole of 20μm in diameter was created through the stainless plate (Thickness: 0.2mm). The roundness of the hole both on the front and back of the plate was excellent, forming smooth edge portions with no chip. A hole of 10μm in diameter was made through a SiC wafer (Thickness: 0.1mm). **Figure 8** shows a hole-drilling sample thereon. An intended hole of 10μm in diameter was successfully created on SiC, which is generally hard to machine due to its bandgap. Further, the quality of the edge portion after drilling is exceptionally high, which indicates that ablation achieved machining with reduced thermal effects.

As described above, due to utilization of the DUV laser beam, optimization of the light-collecting system and precise control of the beam trajectory, high-quality hole-drilling of

20μm or 10μm in diameter and an aspect ratio of 10, which conventionally had been very hard, was successfully achieved. In the future, hole-drilling, cutting and slit-curving will be performed with other dielectric materials, semiconductors and metal materials in order to clarify the superior applicability of the DUV laser by optimizing the machining conditions.

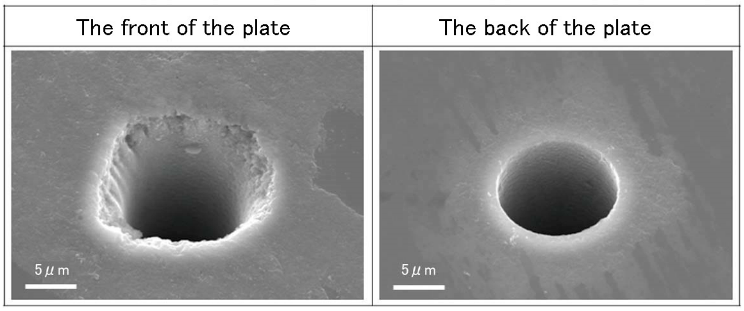

Figure 8 SEM images of hole on a single-crystal silicon carbide wafer drilled with DUV laser
Material: single-crystal SiC wafer, Thickness: 0.1mm, Drilled hole diameter:10μm

4. Conclusion

In order to satisfy the need for finer laser micromachining, MAT has developed an optical system utilizing a short-pulse DUV laser with which MAT confirmed that a micro focused laser spot diameter can be achieved while maintaining the required focal depth. Furthermore, machining characteristics with various different materials were identified by utilizing this new optical system. In addition, MAT installed this optical system in an “ABLASER” laser micromachining system manufactured and sold by MAT, and achieved ultrafine hole-drilling of a minimum of 10μm in diameter and an aspect ratio of a maximum of 10. An ABLASER equipped with the short-pulse DUV laser that is introduced in this paper will be exhibited and sold at the 28th Japan International Machine Tool Fair (JIMTOF 2016). MAT will strive to continue technical development in the future so that we will be able to offer optimal solutions to satisfy the need for finer micromachining with higher quality in various industrial fields.

References

1. Ikeda, N. et al., Diode-Pumped Solid-State Ultraviolet Laser Micro Processing System, Mitsubishi Heavy Industries, Ltd. Technical Review Vol. 40 Extra No. 2 (2003)
2. Nakagawa, K. et al., Microdrilling Technology using Short Pulsed-laser, Mitsubishi Heavy Industries Technical Review Vol. 52 No. 3 (2015)