

Through Hole Forming Method Using a Flowable Backing Material During Pulse UV Laser Radiation

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This paper presents a unique through hole forming method using a flowable backing material during pulse UV laser radiation. During the laser radiation, the backing material such as polymer material solution is arranged to be in contact with the back side of a target material (workpiece), i.e., surface of laser beam's exit side. This unique through hole forming method can easily control the shape of a through hole, e.g., formation of a through hole having straight shape in which the exit hole diameter on the laser beam exit side of the processing target is equal to the entrance hole diameter on the laser beam incident side, or formation of a through hole having so-called inverse tapered shape where the diameter of a formed through hole on the laser beam exit side is larger than the incident side.

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1. Introduction

The ability to produce accurate holes within tight dimensional tolerances is an important aspect of tiny hole application such as nozzle for chemical fibers [1], fuel injection nozzle [2], printed wiring board [3], semiconductor tester [4], optical connector [5] and so on. In pace with advances in electronics, ever-smaller holes in the printed wiring board are required. Tiny holes in the printed wiring board are able to mount electronic parts on the board at high density by improving wiring density. Medical devices such as catheters [6] and etc also demand smaller holes. Tiny holes in catheters make drug delivery possible. By carefully tailoring density and size of holes, the infusion of an active drug can be controlled.

Among numerous methods of hole production existed, mechanical drilling [7], chemical etching [8] and laser machining [9] are the most widely used. However, as the dimension of the hole decreases, choice of process becomes limited. Laser drilling is very common in both electronics and medical device industries. By selecting the right laser for a given application, fine micron-sized features can be produced very economically. Pulsed lasers allow the user to control the amount of energy delivered to the workpiece carefully, making it possible to control a laser drilling process precisely.

Using lasers to drill small holes in the devices mentioned above has many advantages. Not only lasers can create repeatable, high aspect ratio holes in diameters as small as 1 μm [10], also the noncontact process does not require additional coolants or lubricants during drilling. The noncontact nature of laser processing is especially

advantageous when machining very thin materials that are too flexible or fragile to undergo a contact machining process. With properly defined laser drilling parameters, it is possible to produce holes with a minimized heat affected zone, thus eliminating postprocessing requirements to create a clean hole. The materials to be drilled and the size of the features required will determine the most appropriate type of laser. Typically, high pulse repetition rate nanosecond UV lasers, i.e., operating at 355 nm or 266 nm, are suitable for drilling most materials, as these wavelengths of UV light are absorbed well by metals and polymers.

In a through hole drilling process, it is generally known that the diameter of the through hole on the laser beam exit side of the processing target is smaller than the incidence side, i.e., the hole is formed in a so-called tapered shape due to the characteristics of the laser beam. Therefore, when formation of more through holes is required to obtain a sufficient opening area, the numerical aperture required in a specified area in the design is limited.

The objective of this study is to machine arrays of reproducible small holes with a high aspect ratio using nanosecond pulse UV laser. In this paper, we will show you a unique through hole forming method. This unique through hole forming method can easily control the shape of a through hole, e.g., formation of a through hole having a straight shape in which an exit hole diameter on the laser beam exit side of the processing target is equal to the entrance hole diameter on the incident side of that, or formation of a through hole having so-called inverse tapered shape where the diameter of a formed through hole

is larger on the laser beam exit side than the incident side, which cannot be obtained by the conventional technology except for using beam rotator. By using this technique, we will be able to make high efficiency filter which has straight shape holes with narrow pitch.

2. Experimental setup

In this study, we used a Q-switched Nd:YAG laser, SureliteII-10 (Continuum, Inc.), for radiation of fourth harmonic wavelength of 266 nm. This laser operates in the TEM00 mode so the beam has a Gaussian distributed intensity profile. This laser is able to generate laser light at a fundamental wavelength (1064 nm), and 532, 355, 266 nm for second, third, fourth harmonic wave respectively. Pulse repetition rate is 10 Hz and pulse duration is 4 - 6 ns (FWHM).

Figure 1 shows the schematic illustration of laser irradiation part. The laser beam of fourth harmonic wave length of 266 nm was focused onto the processing target using plano-convex lens with a nominal focal length of 50 mm and hit the surface of processing target perpendicularly in air. The diameter of focus spot was measured to be 18 μm by using the burnt pattern of heat sensitive paper. Here, a focal point was set to the front side of the processing target which means the laser beam incidence side. The processing target was fixed on X-Y-Z stage that was driven by the stepping motor controlled by computer. Focus position of the laser beam relative to the target surface was controlled by the Z stage and fixed during the laser radiation. Percussion drilling was used to make through holes.

Commercially available resin materials, i.e., transparent PET sheet and metallic decorative sheet, were used as the processing target. During the laser radiation, either solution of polymer material or colloid solution of polymer material was used as the flowable backing material to obtain expanding effect of an exit hole diameter. The flowable backing material with a range of 50 μm to 2000 μm in thickness was arranged to be in contact with the back side of the processing target, i.e., the surface of laser beam exit side.

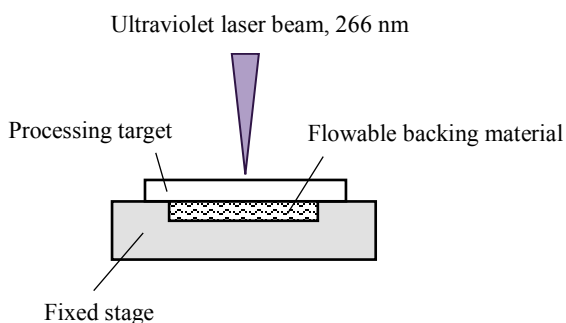


Figure 1 Schematic illustration of laser irradiation part.

3. Experimental results and discussion

Figure 2 shows optical photographs of entrance and exit holes drilled in the transparent PET sheet. The PET sheet

used in this study consists of two layers, that is, a surface layer of light cured acrylic hard coat having a thickness of 10 μm and a foundation layer of PET having a thickness of 38 μm. Thus, total thickness of the PET sheet is 48 μm. The pulse energy of the laser beam 266 nm was set to 10 μJ and the energy fluence of 3.9 J/cm² was achieved at the focal point. The number of laser radiation per hole was set to 105 shots. A commercially available aqueous synthetic glue (hereinafter referred to as PVA glue) which is the solution of polymer material containing polyvinyl alcohol (PVA) was used as the main component of the backing material. To compare the effect of application of PVA glue, through hole forming processing was also performed without using PVA glue. The diameter of each through hole formed on the entrance and the exit surfaces of the PET sheet was measured using an optical microscope, and the measured value and exit/entrance ratio are shown in Figure 2. The exit/entrance ratio is obtained by dividing the exit diameter by the entrance diameter (an average value in any case). A through hole having a straight shape in which an exit hole diameter is equal to an entrance hole diameter is formed when this ratio is 1, a through hole having a tapered shape in which the hole diameter is narrowed toward the exit surface is formed when this ratio is smaller than 1, and a through hole having an inverse tapered shape in which the hole diameter increases toward the exit

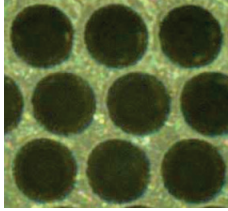
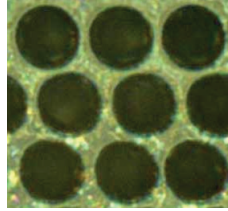
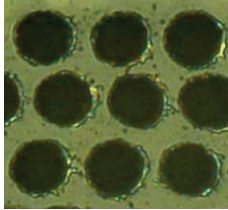
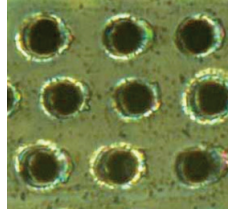
	With PVA glue	Without PVA glue
Entrance surface	 20.7 μm	 20.7 μm
Exit surface	 17.8 μm	 13.8 μm
Exit/Entrance ratio	0.9	0.7

Figure 2 Optical photographs of entrance and exit holes in the transparent PET resin sheet having a thickness of 48 μm. Through holes formed with or without using PVA glue are compared.

surface is formed when this ratio is larger than 1.

As shown in Figure 2, the results where PVA glue is applied and PVA glue is not applied had substantially the same hole diameter on the surface of the laser beam incident side, i.e., the entrance surface of the PET sheet. In both situations, a difference point among the experimental conditions is just the presence or absence of the backing material and the conditions such as the incident laser beam diameter and the focal point which affect the entrance hole

diameter are same. Therefore, it is reasonable that the same entrance hole diameter is obtained in both results. On the other hand, an average hole diameter on the surface of the laser beam exit side in the result where PVA glue is applied had increased by 4 μm compared to the result where PVA glue is not applied. Hence it is confirmed that the expanding effect of the hole diameter on the surface of the laser beam exit side can be obtained. As a result, the exit/entrance ratio is close to 1 when PVA glue is applied during the through hole forming processing. This means that a through hole having a substantially straight shape which is slightly pinched on the exit surface is formed with using PVA glue. Since PVA glue has properties that it is readily dissolved in warm water of temperature from 40 to 80 $^{\circ}\text{C}$, it can be easily removed by cleaning the processing target with warm water after laser processing.

The PET sheet having through holes formed under PVA glue application was cut and its cross section was

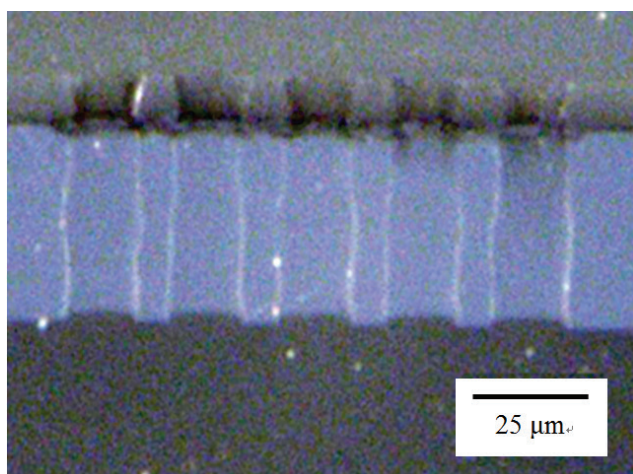


Figure 3 SEM photograph of the cross section of the PET sheet having a thickness of 48 μm .

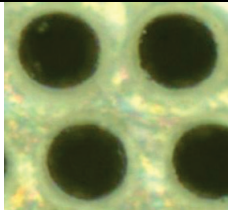
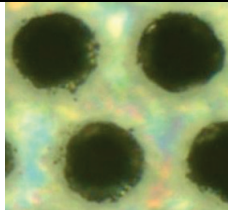
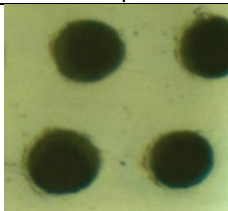
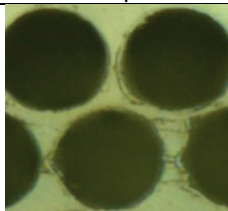
	150shots /hole	900 shots /hole
Entrance surface	 19.0 μm	 19.3 μm
Exit surface	 15.9 μm	 25.2 μm
Exit/Entrance ratio	0.8	1.3

Figure 4 Optical photographs of entrance and exit holes in the transparent PET resin sheet having a thickness of 60 μm . Woodworking adhesive as the colloid solution of polymer material is in contact with the back side of the PET sheet.

observed using Scanning Electron Microscope (SEM). The cross section is shown in Figure 3. The upper part of this figure is the laser beam incident side, i.e., the entrance surface of PET sheet. It can be understood from this figure that each formed through hole has a cylindrical shape where the inner diameter at a central portion is equal to the hole diameter in the entrance and exit surfaces. The hole wall was also continuously formed between the light cured acrylic hard coat layer having a thickness of 10 μm and the PET layer having a thickness of 38 μm .

Figure 4 shows the result obtained from transparent PET resin sheet with a thickness of 60 μm . In this sheet, the surface layer of light cured acrylic hard coat is 10 μm in thickness and the foundation layer of PET is 50 μm in thickness. The pulse energy of the laser beam 266 nm was 5 μJ . The number of laser radiation per hole was set to 150 shots and 900 shots. In this experiment, a commercially available sol type water dispersible woodworking adhesive (hereinafter referred to as woodworking adhesive) containing polyvinyl acetate as main component was used as the backing material. It can be understood from this figure that when the woodworking adhesive is arranged to be in contact with the back side of the PET sheet, each diameter of exit hole increases by the increase in laser radiation number, i.e., the increase of contacting time of the laser beam and the backing material. When the number of laser radiation is 900 shots per hole, the through holes having the inverse tapered shape are formed.

Figure 5 shows a SEM photograph of cross section of the PET sheet shown in Figure 4 at the number of laser radiation 900 shots per hole. The upper part of this figure is the entrance surface of the PET sheet. As shown in this figure, each formed through hole has a circular truncated conical shape where the hole diameter in the exit surface is slightly larger than the hole diameter in the entrance surface. The hole wall was also continuously formed between the light cured acrylic hard coat layer having a thickness of 10 μm and the PET layer having a thickness of 50 μm .

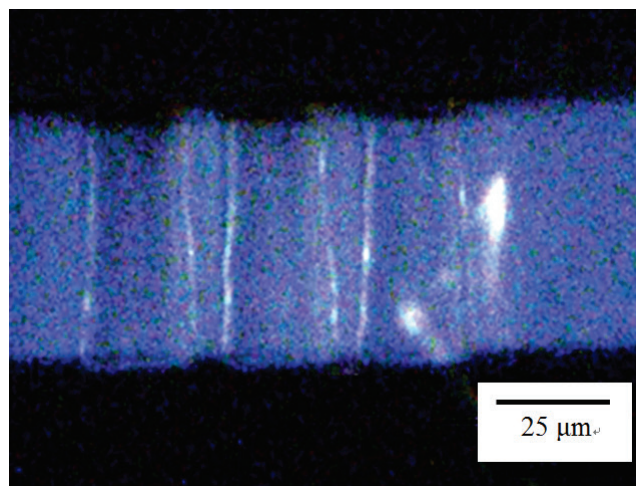


Figure 5 SEM photograph of the cross section of the PET sheet having a thickness of 60 μm .

Figure 6 shows the result obtained from a metallic decorative sheet with the thickness of 205 μm. The metallic decorative sheet is obtained by sequentially laminating a polyester film having a thickness of 50 μm, a chromium metal layer having a thickness of 40 nm, an urethane based adhesive layer having a thickness of 5 μm and an olefin-based thermoplastic elastomer film having a thickness of 150 μm in the mentioned order. The surface of

the laser beam exit side was provided on the polyester film side and PVA glue was applied to this surface. The pulse energy of the laser beam 266 nm was set to 20 μJ. The number of laser radiation was 1,050 shots for each hole. It can be understood from this figure that, when PVA glue is applied to the surface of the laser beam exit side of metallic decorative sheet, each hole diameter obviously increased, and the through holes having the inverse tapered shape were formed.

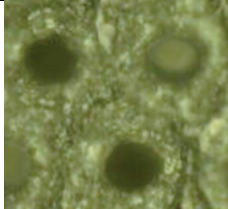
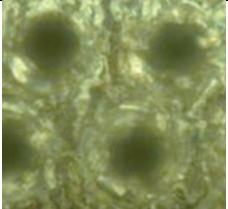
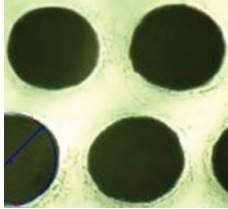
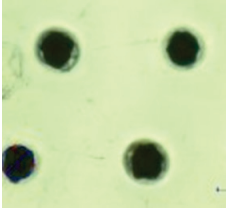
	With PVA glue	Without PVA glue
Entrance surface	 20.7 μm	 20.2 μm
Exit surface	 34.5 μm	 13.0 μm
Exit/Entrance ratio	1.7	0.6

Figure 6 Optical photographs of entrance and exit holes in the metallic decorative sheet having a thickness of 205 μm. The number of laser radiation per hole was 1,050 shots. Through holes formed with or without using PVA glue are compared.

To confirm the relationship between the pulse energy and the hole shape that differs depending on the number of laser radiation, through hole forming processing was carried out under the following conditions. The processing target was metallic decorative sheet with a thickness of 205 μm. PVA glue was applied as the backing material. The pulse energy of the laser beam 266 nm was increased from 7 μJ to 20 μJ. The number of laser radiation was also increased from 150 shots to 1,050 shots per hole. Average hole diameters on the entrance and the exit surfaces of the metallic decorative sheet after through hole forming were measured, respectively. Moreover, the metallic decorative sheet without using PVA glue was examined at the pulse energy of 20 μJ for reference purpose.

The result is shown in Figure 7. This figure shows each relationship between the number of laser radiation per hole and the hole shape in terms of the ratio obtained by dividing the exit hole diameter by the entrance hole diameter. This drawing shows that through hole having a straight shape in which the exit hole diameter is equal to the entrance hole diameter is formed when an ordinate ratio is 1, while through hole having tapered shape that is pinched toward the exit surface is formed when the

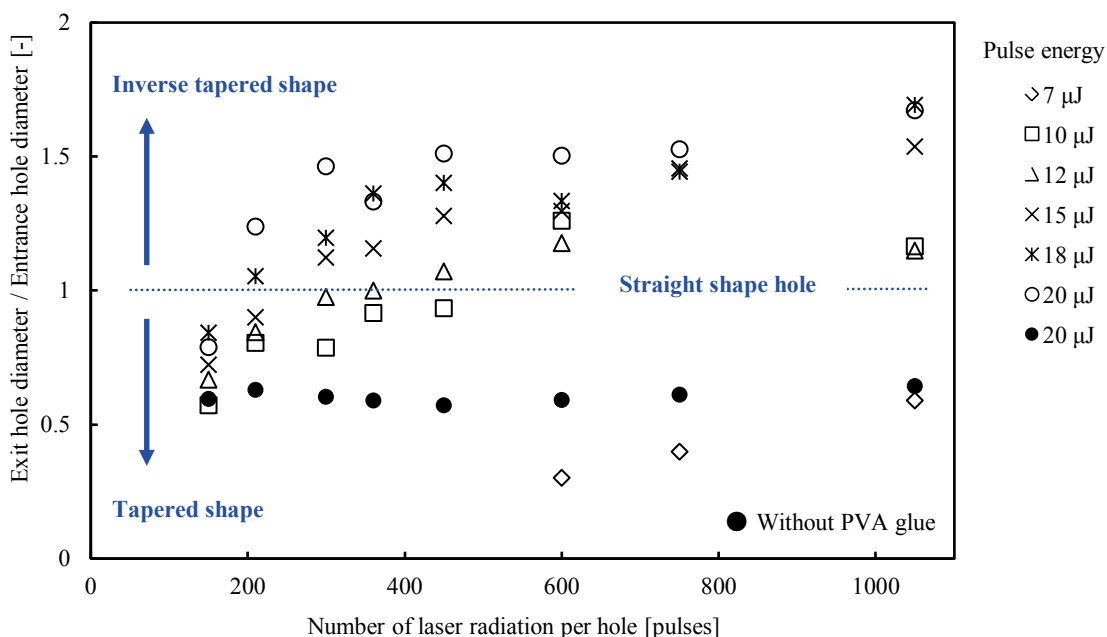


Figure 7 Relationship between the number of laser radiation per hole and a hole shape (a ratio of exist hole diameter/entrance hole diameter). The processing target is the metallic decorative sheet having a thickness of 205 μm. PVA glue is in contact with the back side of the metallic decorative sheet.

ordinate is smaller than 1, and through hole having an inverse tapered shape that expands toward the exit surface is formed when the ordinate is larger than 1. At the result where PVA glue was applied, although each incidence hole diameter increased in accordance with the pulse energy, it was not influenced by the number of laser radiation. On the other hand, the exit hole diameter increased with increasing in the number of laser radiation at each pulse energy in where PVA glue was applied, whereas the exit hole diameter rarely changed even though the number of laser radiation rose in where PVA glue was not applied (black circles in Figure 7). Therefore the ratio of the exit hole diameter to the entrance hole diameter increases with increasing in the number of laser radiation at each pulse energy except for the case without PVA glue. Further, comparing the pulse energy required for processing the same through hole in terms of the exit hole diameters, the result where PVA glue was applied to the back side of the metallic decorative sheet enabled the processing with the pulse energy which was approximately half of the result where PVA glue was not applied. Hence, the energy saving process could be realized using the backing material such as PVA glue. Based on Figure 7, when PVA glue is applied to the surface of the laser beam exit side during the through hole forming process, each desired through hole having the tapered shape, straight shape or inverse tapered shape can be formed, in other word, shape of the hole can be adjusted.

As mentioned above, we used PVA glue and woodworking adhesive as the backing material in this study. Why does the exit diameter of the through hole expand when the backing material is arranged to be in contact with the back side of the target material? The reason yet remained unclear, nevertheless, we consider that plasma formed as a result of absorption of the laser beam to the backing material is the main cause of the phenomenon. In order to examine the effect of the absorption rate of the laser beam to the backing material, laser beam of different wavelength, i.e., fundamental wave, second harmonic wave and third harmonic wave of a Q-switched Nd:YAG laser with pulse duration of 4 - 6 ns, SureliteII-10, were irradiated to the metallic decorative sheet with the thickness of 205 μm . PVA glue was used as flowable backing material during the laser radiation. When fundamental wave or second harmonic wave was irradiated to the metallic decorative sheet, the exit diameter of the through hole did not expand even though backing material was used. In the situation of third harmonic wave, the exit diameter of through hole expanded even though part of the edge of the exit hole had melted. In general, light absorption rate of the substances is higher in the UV region. Therefore the superheated plasma is expected to be generated by the reaction of UV laser beam and the backing material around the exit hole. The hydrolysis reaction of the polymers was reported by S.Homma [11]. In his paper, it is stated that the polymers which have ester bond to a molecular frame such as PC, PBT and PET will cause hydrolysis and when the temperature rises, hydrolysis becomes remarkable. It also states that the polymers are hydrolyzed by a small amount of water in the

melting temperature range. We consider that the hydrolysis is one of the mechanism of expanding the exit hole's diameter.

We also focus our attention on the existence of the hydroxyl group (-OH) in the backing material. PVA glue is the solution of polymer material containing polyvinyl alcohol. The sol type water dispersible woodworking adhesive contains polyvinyl acetate and is produced by emulsion polymerization of vinyl acetate monomer containing poval as the protective colloid. The chemical name of poval is polyvinyl alcohol. Thus, the water dispersible woodworking adhesive also contains polyvinyl alcohol. Polyvinyl alcohol has the hydroxyl group in the molecule as shown in Figure 8. We consider that the hydroxyl group reacts with UV laser beam to form hydroxyl radical [12]. The Hydroxyl radical takes an electron from an organic compound nearby, and itself becomes stable. The organic compound which lost an electron catches the reaction such as the cutting of the chemical bond and it decomposes. In order to clear the reaction between the laser beam and the flowable backing material, we need to measure the plasma emission. But the measurement of the plasma emission is very difficult because the phenomenon occurs at the back side of the target material, we have not measured it yet.

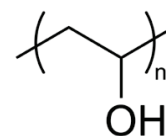


Figure 8 Chemical formula of polyvinyl alcohol.

4. Conclusions

A new approach to through hole forming was demonstrated to produce through hole of the straight shape or the inverse tapered shape in resin materials. The through hole having the straight shape and the inverse tapered shape were successfully fabricated when either solution of polymer material or colloid solution of polymer material was arranged to be in contact with the back side of the target material during the laser radiation. This unique through hole forming method can easily control the shape of a through hole.

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