Liquid-Assisted Excimer Laser Micromaching for Ablation Enhancement and Debris Reduction

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Previous studies demonstrated that laser ablation under transparent liquid can result in ablation enhacement and particle removal from the surface. In this work, the liquid-assisted excimer laser ablation process is examined for polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), Si, and alumina with emphasis on ablation enhacement, surface topography, and debris formation. In the case of PET and PMMA, the effect of liquid is analyzed both for thin water film and bulk water. As the ablation enhanement by liquid is already known for Si and alumina, the analysis focuses on surface topography and debris formation resulting from the liquid-assisted laser ablation process. A KrF excimer laser is utilized for ablationg the materials in the fluence range 1~10 J/cm^2. The results show that application of liquid increases the ablation rate of PMMA while that of PET remains unchanged even in the liquid-assisted process. It is also revealed that the liquid can significantly improve the surface quality by reducing the debris deposition. However, the surface roughness is generally deteriorated in the liquid-assisted process. The surface toporaphy is found to be strongly dependent on the method of liquid application, i.e., thin film or bulk liquid.

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1. Introduction

It has been reported that high-power laser irradiation on a solid surface covered with a liquid layer can produce a strong shock wave in the solid since the liquid layer confines the plasma [1,2]. Previous studies have also revealed that laser ablation under neutral, i.e., transparent, liquid results in significant enhancement in the ablation rate [3-6]. Meanwhile, investigations on the steam laser cleaning process have demonstrated that thin liquid film deposited on a solid surface removes submicron particles effectively from the surace via explosive vaporization of the applied liquid [7-9]. Consequently, it is evident that laser ablation in the liquid environment provides a number of unique feastures, which may be employed in material processing applications.

In this work, excimer laser ablation of PET, PMMA, Si, and alumina (Al_2O_3) is examined in the presence of a trasparent liquid layer on the surface, for possible applications in laser micromachining processes. Excimer laser micromachining is a clean, safe, and flexible process for microfabrication of precision parts and devices, especially for polymer materials. Nevertheless, low ablation rate for hard-to-process materials, such as ceramic and metallic materials, and degradation of the surface quality by the ablation debris formation at high fluences and often cast serious limitations. Since applying a liquid layer generally increases the ablation yield and reduces debris formation, analysis of the effect of liquid on the excimer laser ablation process is thus of great interest. Furthermore, despite the previous investigation as summarized above, understanding the physics of laser ablation in the liquid environment is still in its beginning stage. Accordingly, ablation of a material in liquid is a subject of scientific significance as well.

PET and PMMA are typical polymer materials widely used in laser micromachining applications and MEMS fabrication. However, to the best of our knowledge, their ablation characteristics in the liquid environment have never been studied. Accordingly, the main objective of the present work is to analyze the liquid-assisted ablation process for the two typical polymers, with emphasis on the ablation enhacement, surface topography, and debris generation. In addition, the change in surface topography and debris production in the liquid-assisted ablation of Si and alumina are also examined in this work since it has not been thoroughly analyzed while enhanced ablation of the materials by liquid is relatively well known [5,6]. Si and alumina are semiconductor and ceramic materials commonly used in a variety applications.

In the liquid-assisted laser processing of materials, several different methods can be employed to apply liquid. For instance, the target can be entirely submerged in the liquid or a thin liquid film can be formed as in the steam laser cleaning process [8]. These different methods are likely to cause different results because pulsed laser ablation is in general strongly depends on the hydrodynamics of the ablation plume and the phase change interface. Consequently, two different methods of liquid application are tested in the present study. In the thin-film case, thin liquid films of several micrometers in thickness are deposited on the surface by condensing the water vapor on the sample. On the other hand, in the bulk-liquid case, the target is entirely submerged in water whose depth can be assumed to be infinitely large.

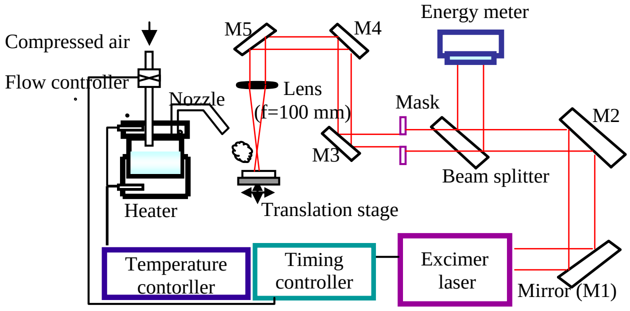


Fig. 1 Schematic diagram of the experimental setup.

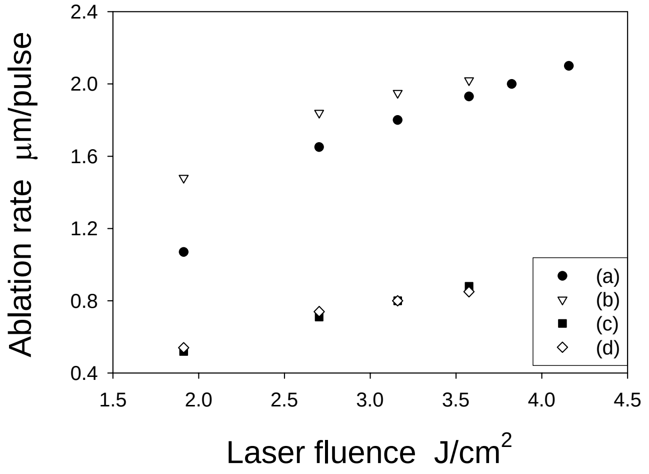


Fig. 3 Ablation rate vs. laser fluence: (a) dry and (b) liquid-film-assisted ablation of PMMA, and (c) dry and (d) liquid-assisted ablation of PET.

2. Experiment

A schematic diagram of the experimental setup is shown in Fig. 1. Polymers (PMMA, PET), Si and Al_2O_3 are ablated by a KrF excimer laser (wavelength λ = 248nm, full width at half maximum FWHM = 25 ns). For attaining a uniform spatial distribution of the laser energy, the excimer laser beam having a Gaussian intensity distribution with an elongated axis was cut off by an aperture and only the core part with a relatively flat intensity distribution was utilized. An optical system forms 4 ~ 12× demagnified images on the sample surface. The laser fluence F and the repetition rate were varied in the range 0.5 ~ 10 J/cm^2 and 0.2 ~ 10 Hz, respectively. Various masks, including a slit of 200 μm in width and pin holes of 200 ~ 2000 μm in diameter were employed for projection micromachining. A three-dimensional precision positioning system manipulates the sample with a positioning resolution of 1 μm. This excimer laser micromachining system is commonly used to produce micro holes and various microscale structures. An example showing typical results obtained by laser micromachining system is displayed in Fig. 2.

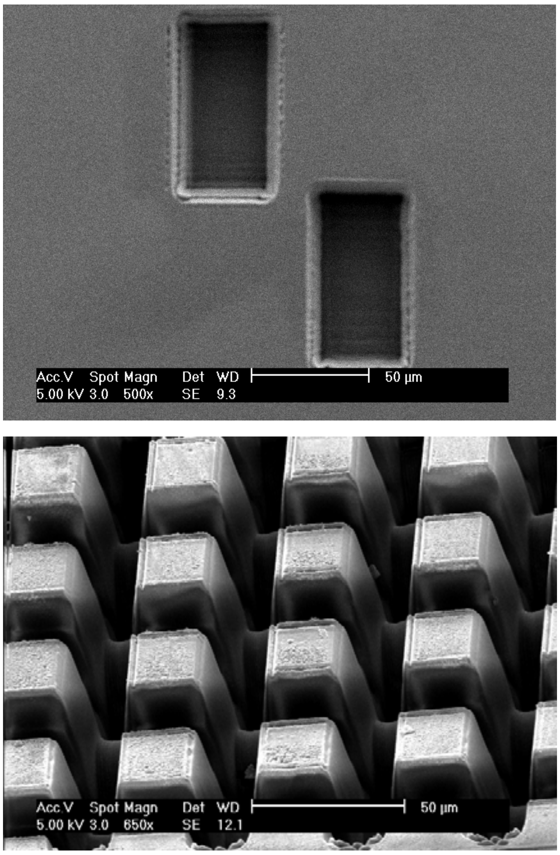


Fig. 2 Examples of micro-structures produced with mask projection method in PET (F=2.1 J/cm^2)..

In the liquid-assisted process using thin liquid film, the liquid layer was deposited by condensing the saturated vapor on the target. A nozzle driven by a high-pressure purified air line injects the vapor onto the target surface and a thin liquid film is produced by condensation prior to the laser pulse irradiation. A heater was used to maintain the temperature of water in the chamber at an elevated temperature around 60 °C. Approximately 10 % of isopropanol is mixed with water to improve the wetting characteristics. The puffing duration for the liquid film deposition was set to be about 50 ~ 100 ms. After a delay of 50 ms, excimer laser was fired onto the sample surface. In the case of the liquid-assisted process using bulk liquid, the sample was entirely submerged in water as shown in Fig. 1.

After laser processing of the materials under variable conditions, the samples were analyzed using an optical microscope, a scanning electron microscope (SEM) and an interferometric surface profiler.

3. Results and Discussions

3.1 Ablation rate for polymers

Figure 3 exhibits the results of the ablation rate measurement for PET and PMMA. The ablation rate shown in Fig. 3 is an averaged value based on multiple pulses up to 10 pulses. Examination on the effect of pulse number reveals that the mean ablation rate does not change with the pulse number in the range up to 10. In Fig. 3, the liquid film does not change the ablation rate of PET. On the other hand, the ablation of PMMA has been considerably enhanced in the liquid-assisted process, especially at low laser fluences. This striking difference suggests that the ablation mechanisms for the two polymer materials are

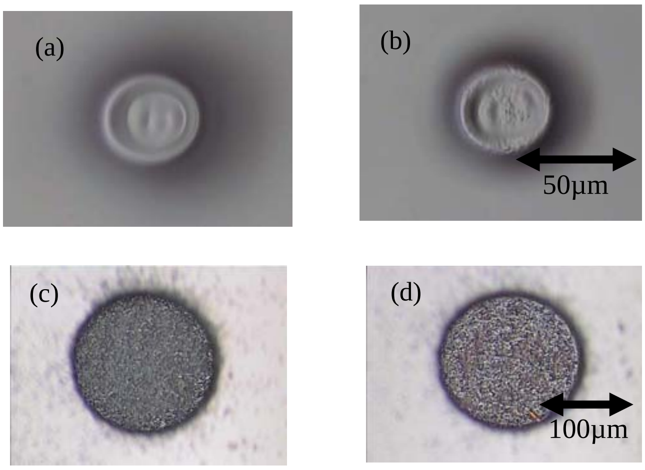


Fig. 4 Surface topography obtaind (a) dry and (b) liquid-film-assisted processes of PET, (c) dry and (d) liquid-film-assisted processes of PMMA at F= 1.9 J/cm^2 with 10 pulses

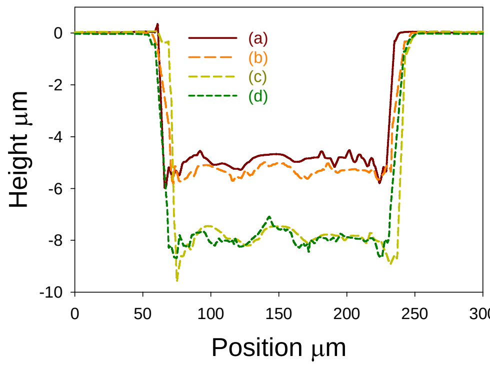


Fig. 5 Surface topography obtained (a) dry and (b) liquid-film-assisted processes of PET, (c) dry and (d) liquid-film-assisted processes of PMMA at F= 1.9 J/cm^2 with 10 pulses

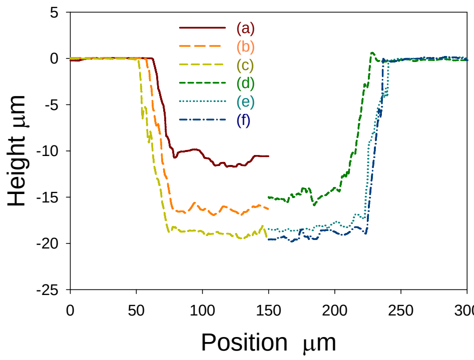


Fig. 6 Surface topography of PMMA obtained in dry laser processing at F : (a) 1.9, (b) 2.7 and (c) 3.6 J/cm^2 and liquid-film-assisted processes at F:(d) 1.9, (e) 2.7 and (c) 3.6 J/cm^2

different to a large degree. If ablation of a polymer by a UV pulse occurs entirely by the photochemical effect, the influence of liquid will be relatively insignificant, compared with a photothermal process in which hydrodynamics of the ablation plume and melt pool is important. Ac-

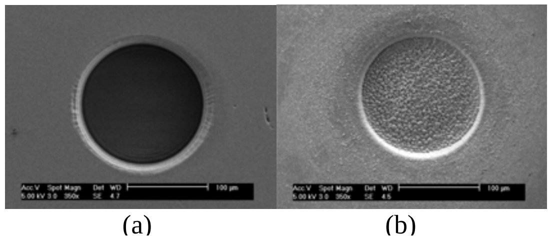


Fig. 7 Surface topography obtained (a) dry and (b) bulk water processes of PET at F=1.9 J/cm^2 with 100 pulses.

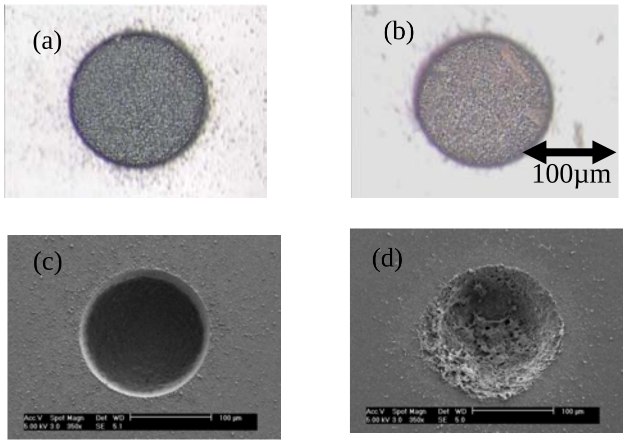


Fig. 8 Surface topography obtained (a) dry and (b) liquid-film-assisted processes with 10 pulses (c) dry and (d) liquid-film-assisted processes of PMMA at F= 1.9 J/cm^2 with 100 pulses.

cordingly, the results in Fig. 3 indicate that the ablation of PET by a UV laser is largely dominated by a photochemical process while that of PMMA is significantly affected by a photothermal effect. The surface formed by excimer laser ablation of PET is smoother than PMMA (see Figs. 5 and 6), which also corroborates the above notion regarding the ablation mechanism of the two polymers.

3.2 Surface topography for polymers

Figure 4 illustrates the surface topography obtained in the dry and liquid-film-assisted processes. The corresponding surface profiles are given in Figs. 5 and 6. In both cases of PET and PMMA, the effect of liquid film on the hole profile is not pronounced though the surface roughness is slightly increased by the liquid film. Comparison of PET with PMMA shows that the surface of PET is relative smooth. The results obtained in bulk water are presented in Figs. 7 and 8 for PET and PMMA, respectively. In both cases, the increase in the surface roughness by the bulk-liquid-assisted process is more substantial than in the liquid-film-assisted process. In the case of PET, a grain-like microstructure having a certain characteristic scale is generated on the ablated surface, increasing the overall roughness. In the ablation of PMMA, in addition to the increased surface roughness, the surface profile has also been changed by liquid considerably, as shown in Fig. 6. Comparison of these results with Fig. 4 manifests that the method of liquid application is critical in determining the

(a) (b)

Fig. 9 Optical microscope image of PET: (a) ablation in air and (b) ablation with liquid film at F=2.3 J/cm^2 (50 pulses).

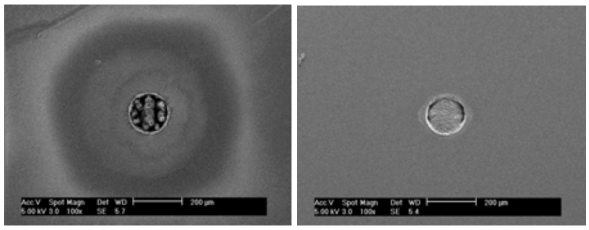
surface topography produced by the liquid-assisted process. It is evident that application of a thin liquid film enlarges the ablation rate with minimized deterioration in the surface topography.

3.3 Debris formation for polymers

When polymers are ablated by a UV laser pulse, various types of debris are generated including carbon soot particles and fragments [10]. The formation of debris is easily identified under an optical microscope, particularly at high laser fluences. Figure 9(a) therefore displays typical micrographs showing debris formation in ablation of PET processing. In Fig. 9(b), reduction of debris formation in the liquid-film-assisted process is depicted. It is clear that the thin liquid film suppresses the debris formation by protecting the surface from the ablation plume. Similar results are obtained for PMMA and for processes using bulk liquid.

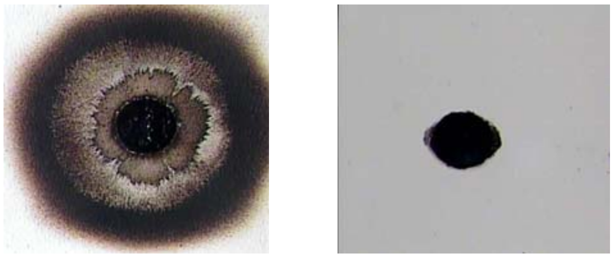
3.4 Liquid-assisted ablation of Si and alumina

The experimental results obtained in this work conform that the liquid-assisted process enhances laser ablation of Si and alumina. Meanwhile, the formation of the ablation debris and peripheral ring-shaped bumps around the hole is substantially reduced in the ablation in water. Figure 10 exhibits the image of the ablation spot for Si. It elucidates that the liquid-assisted process leads to more uniform surface topography with reduced waviness and bump formation. Optical micrographs in Fig. 11, attained to visualize the debris formation, reveal that the liquid-assisted process remarkably diminishes the debris formation around the ablation spot. Largely similar results are obtained for Al_2O_3 and the results are shown in Fig. 12. In the case of alumina, the elimination of the peripheral bump is more pronounced than Si.



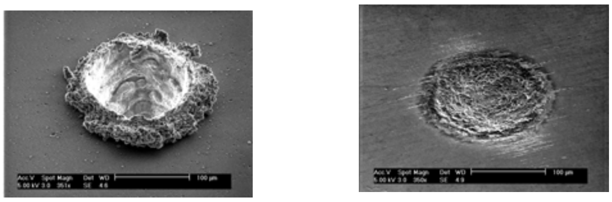
(a) (b)

Fig. 10 SEM image of Si: (a) ablation in air and (b) ablation with liquid film at F=4.2 J/cm^2 (500 pulses).



(a) (b)

Fig. 11 Optical microscope images of Si: (a) ablation in air and (b) ablation with liquid film at F=4.2 J/cm^2 (500 pulses).



(a) (b)

Fig. 12 SEM images of Al_2O_3: (a) ablation in air and (b) ablation with liquid film at F=4.2 J/cm^2 (100 pulses).

4. Conclusions

In this work, the liquid-assisted excimer laser ablation process has been analyzed for PET, PMMA, Si, and alumina. The following conclusions can be drawn form the experimental results:

(1) Ablation is enhanced by liquid for PMMA while no enhancement is archived by liquid for PET. The enhancement is pronounced particularly at low laser fluences.
(2) Liquid film does not change the surface topography of polymers considerably but bulk liquid seriously deteriorates the topography of the ablated spot with formation of microscale grain-like structures.
(3) Debris formation on polymers in laser micromachining can be significantly reduced by applying liquid in all cases.
(4) Liquid can substantially improve the surface quality (topography, bump, debris, etc.) in excimer laser ablation of Si and Al_2O_3.

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