Letter

Generation of Energetic Liquid Jet and Atomization by Pulse Laser Reflection at Inclined Surface of High Refractive Index Material

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Abstract

In previous studies, we have shown the appreciable reduction of pulse laser ablation threshold by laser beam reflection at the transparent material interface with air. In this study, we have tested a similar situation but using transparent energetic and non-energetic liquids in air. Whole ablation and subsequent atomization processes were observed by pulse laser shadowgraphy.

Minimum laser fluence for laser ablation at water-air interface is found to be around 12-16 Jcm^{-2}. Several kinds of liquid samples tested in the present study include water, ethanol, engine oil and kerosene. It is found that liquid atomization process is quite similar for several liquid samples, and all the energetic liquids tested can be ignited by a heated NiCr wire above the liquid surface.

Keywords : Pulse laser ablation, energetic liquid, liquid jet, atomization, combustion

1. Introduction

Authors have studied enhancement of pulse laser energy absorption on the intentionally roughened surface of transparent materials.[1),2)] We have found that phenomena depend on the direction of laser irradiation direction. Appreciable reduction of laser ablation threshold takes place only when the laser beam is irradiated through the transparent material onto the roughened surface. Especially from the studies of pulse laser ablation of ground glass, it is found that burst of small fragments of glass has been observed, when ground glass surface is laser ablated through glass plate from rear side.[3),4)] From the previous studies it is confirmed that the phenomena can be explained at least qualitatively by the transmission-reflection law at material interface with different refractive indices.[3)-5)] If this is generally the case, similar phenomena can be expected at the interface of liquid and air due to the difference of their refractive index.

In this paper, we will intend to apply the same idea to the interface of liquid surface on air. As shown in later sections, reflection of pulse laser beam at the liquid-air interface could induce liquid jetting followed by the atomization process. Area of application of this phenomena includes liquid fuel atomization, and drug and/or gene delivery, etc.[6)] One of our purposes of the present study is to investigate the reaction phenomena of emerging energetic liquid jet produced by this process.

2. Experimental

According to the results of the previous studies, laser ir-

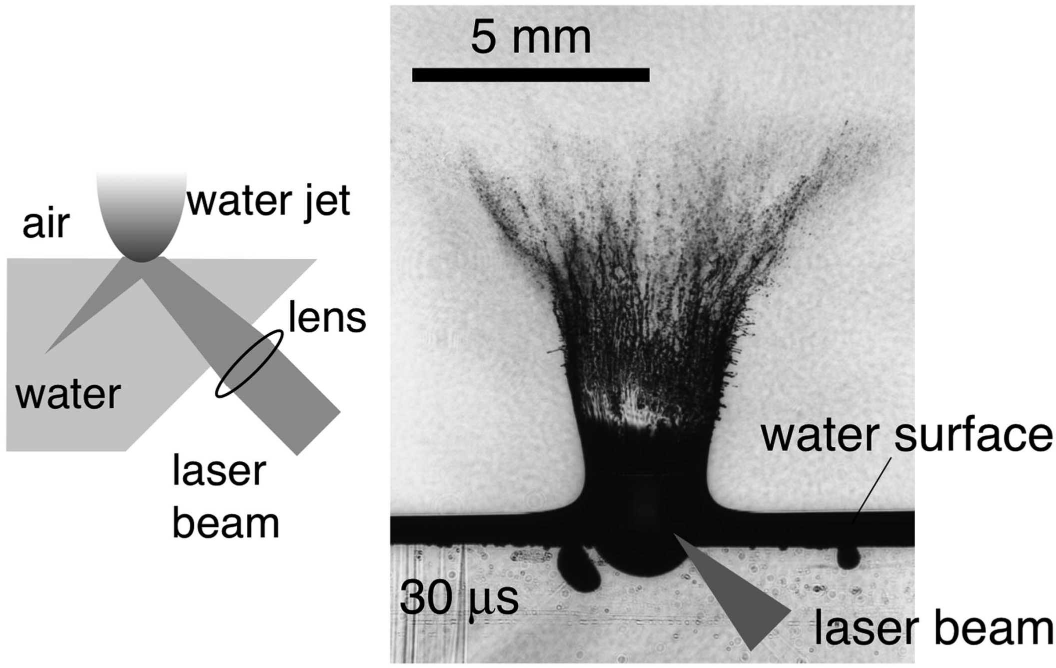

Fig. 1 Schematic of experimental assembly and laser shadowgraph reproduction of the laser ablation of water surface. Laser beam is focused from bottom right to the air interface and reflected to the breakdown region. Delay time of the record is shown in the photograph. Laser energy is 300 mJ and laser fluence is calculated to be 20 J cm^{-2}.

radiation inside liquid medium onto the air interface with somewhat large angle close to or over the critical angle of total internal reflection should give appreciable reduction of ablation threshold of liquid.

We have used an Nd : YAG laser of 10 ns duration, 300 mJ energy and of wavelength 1064 nm. Laser beam was focused from bottom right of the liquid container in order to reflect at the liquid−air interface and to have a focus in a region inside liquid after reflection. Laser fluence is adjusted to be low enough not to occur breakdown of liquid at the area before or at the liquid surface. To observe the whole process, we have adopted pulse laser shadowgraphy as a method of observation of the phenomena. We have used another Nd : YAG laser with SHG crystal as a light source. Use of high resolution film is the key in this method. Minicopy film of FUJI Film Co. with 850 lp mm^{-1} for the document copy is used. Small aperture is inserted between two objective lenses to avoid exposure of the film by the flash caused by laser ablation of the liquid surface.

For the observation of the ignition behavior, a heated NiCr wire was placed 30 mm above the liquid surface. High−speed video camera of Phantom V4.2 was used to observe the ignition when the atomized energetic liquid passes the heated wire.

3. Results and Discussion

We have started the experiment on the water−air case. We estimated the value of fluence at the interface by considering that the laser irradiated area is not circular but oval in shape due to the angle of incidence of about 45 degrees as shown schematically in Fig. 1. It is shown that the minimum laser fluence of surface ablation will take place at about 12−16 J cm^{-2} in our case. It is found from the experiment that instantaneous energy deposition at the water surface leads to the production of plasma and water vapor and eventually water droplet. Slender splashes extends from water surface at later delay pictures.

Figure1 shows typical shadowgraphs in case of water and air interface. Since very tiny water splashes on the water vessel wall play deflect parallel laser beam and recorded as black circles on the film, very careful cleaning and preparation is necessary to obtain the reproducible images.

Air shock wave front is precedent on the ligaments. Successive pictures of different delay time showed that direction of ligament extension will change with time, so that flower like structure is formed in these frames. It is easily expected that liquid atomization takes place at the tip of the ligaments together with large droplets. In this sense, the phenomena resembles to the liquid jet emanating from the diesel nozzles.

In order to proceed to the similar ablation experiments using energetic liquid materials, we have used an experimental assembly shown in Fig. 2. Figure 2 also contains high resolution shadowgraphs by pulse laser for the ablation of thin ethanol layer on glass plate. It is found that all the liquids tested in the present study can be ablated by the similar experimental conditions.

In the case of the energetic liquid ablation, we have adopted an experimental assembly as shown schematically in Fig. 2. Laser beam was introduced from water layer to the glass plate and finally to the liquid drop of energetic material on the glass plate. Due to the high vapor pressure of the energetic liquids, this configuration is inevitable to maintain the liquid surface in order to adjust the specified value of laser fluence. Incident angle of the pulse laser beam is set to that of critical angle of water air interface. The incident angle at the energetic liquid air in-

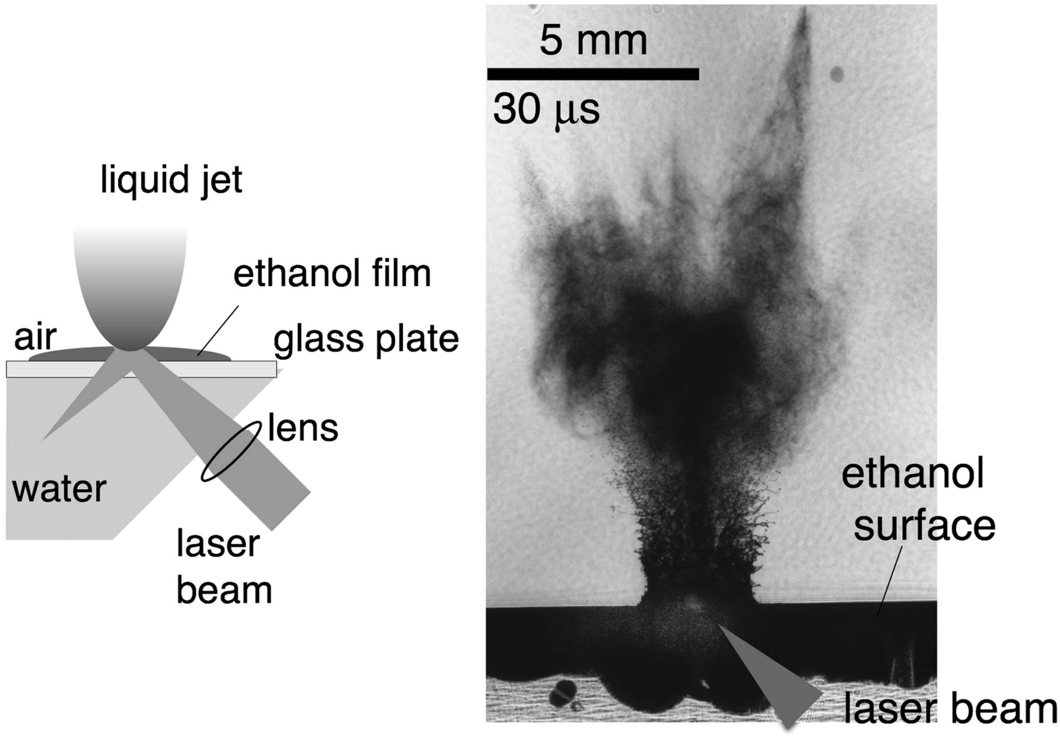

Fig. 2 Schematic of experimental assembly and laser shadowgraph reproduction of the laser ablation of ethanol surface. Delay time of the record is shown in the photograph. Laser energy is 300 mJ and laser fluence is calculated to be 20 J cm^{-2}.

terface is then automatically equal to the critical angle of these two media. Although some loss of laser energy is expected due to the reflection at water–glass and glass–energetic liquid interface, it is shown in this study that ablation phenomena takes place. We are considering the resemblance and difference of the present phenomena with the phenomena of milk crown induced by the liquid drop impact on a thin liquid layer.

One may compare the pictures of water and ethanol surface ablation included in Fig. 1 and 2. Expanded liquid jet of water and ethanol shown in Fig. 1 and 2 seems quite different. Expansion direction of the jet of ethanol is somewhat more close to the surface normal compared with that of water jet. It is noticeable that very small liquid drops observable by the present film record is diverse in case of water, while in case of ethanol it is hard to see wide spread particle distribution. This may be due to the fact that the small particles produced by ablation evaporates during expansion. The present results may have important, if one will use the phenomena to ignite the evaporated vapor and liquid droplets cloud.

As a preliminary test of the present ablation phenomena to apply to the fundamental liquid fuel supply process for combustion or deflagration, we have made simple ignition experiments. Wound NiCr wire is joule heated to ignite the energetic liquid plume. It was placed 3cm above the liquid surface. To avoid premature combustion of liquid samples, electric current supply to the NiCr wire was triggered slightly before the laser irradiation, since some of the liquid samples have high evaporation pressure to induce self ignition by the hot wire.

Ignition and combustion process was observed by high–speed video camera. It is found that ignition takes place at least after 500 μs delay time after laser ablation. This result indicates that the combustible vapor mixture of liquids will travel 3cm between liquid surface and NiCr wire by the average velocity of around 60 m s^{-1}. The timing of ignition identified by video records is almost the same for all the energetic liquid samples.

4. Summary

We have discovered novel ablation phenomena at the interface of two fluid media, if the pulse laser is focused from material of higher refractive index to that of lower one. Due to the nature of fluids, not only plasma plume but also bulk liquid jetting and flows are induced by laser energy deposition at the interface layer.

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高い屈折率の物質の傾いた面でのパルスレーザーの反射による液体状エネルギー物質ジェットの発生と微粒化

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これまでの研究から我々は，透明材料と空気の界面でのレーザービームの反射によりパルスレーザーアブレーション閾値の大きな低下を確認した。本研究では，同様の場合について試験した。ただし，透明なエネルギー物質および非エネルギー物質の液体と空気の界面の条件である。アブレーション現象とそれに続く微粒化過程はパルスレーザーシャドーグラフ法により観測された。

おこなった実験条件の範囲で水－空気系のアブレーションに対するレーザーフルーエンス閾値は12-16Jcm^{-2}で程度であることがわかった。本研究では，水，エタノール，エンジン油，灯油を含む数種類の液体試料を用いた。液体の微粒化特性はいくつかの液体試料についてほぼ同等であり，試験したすべてのエネルギー物質は液体表面の上方にある加熱ニクロム線により着火可能であった。

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