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Time-resolved observation for dynamic evolution of plasma produced by multiple laser pulse exposure to metallic surface

Peng Gu, Shi-Bing Liu*, Song Liu, Hai-Ying Song

Strong-field and Ultrafast Photonics Lab, Institute of Laser Engineering, Beijing University of Technology, Beijing 100124, China

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ABSTRACT

Pulsed laser ablation of solid target has very wide applications in many areas at present. However, most theoretical and experimental investigations focus on the interaction between pulsed laser and solid target with flat surface. It is significant for practical application of pulsed laser to research it interact with a non-smooth target surface. In this paper, time-resolved observation using ICCD camera has been performed to research process of plasma induced by nanosecond laser pulse ablation of copper target with a rough plaque. The experiment result shows the copper target is ionized at first and plasma plume then produce. Moreover, the plasma plume produce again at the end of the laser pulse because large amount of particles moves towards the target and transfer energy to the surface resulted in ionization.

1. Introduction

Nanosecond laser ablation of solid target has many current applications in different areas such as deposition of thin films, micromachining, and laser-induced breakdown spectroscopy (LIBS) [1–3]. A plasma plume is often produced in these applications, whose evolution may be a critical process during nanosecond laser pulse interaction with material. Although most previous studies have been devoted to nanosecond laser pulse ablation on a flat surface [4–7], it is more common in many applications that repetitive pulses irradiate the same target location. As a result, the nanosecond laser pulse interaction is with the non-smooth target surface, rather than the flat surface. The amount of energy absorbed by target with a cavity is greater than the energy absorbed by a flat surface according to thermal radiation analysis [8] and numerical calculations [9]. Therefore, the evolution of plasma induced by laser ablation on a non-smooth target surface must be different from a flat surface. Despite some theoretical investigations, numerical calculations and experiments on nanosecond laser ablation of solid target with a cavity structure have been done [8–11], the study for evolution of laser-induced plasma from a non-smooth target surface is limited [12,13]. Furthermore, many researchers often use ultraviolet (UV) or visible and short nanosecond lasers (with durations less than 30–50 ns) in these experiments.

In this paper, we use long ns laser pulses (with durations of 100 ns) to ablate copper target with a rough plaque (RP) to induce plasma and the time-resolved observation is performed for this work. The expansion process of laser-induced plasma is captured using an ICCD camera coupled with a microscope tube. The experimental result and the analysis can reveal the physical mechanism of plasma evolution for repetitive laser pulses copper ablation process.

2. Experimental setup

The experimental system used for this study is presented in Fig. 1. A Nd:YAG laser can generate a 100 ns(full pulse duration) laser pulse at 1064 nm. The laser pulse repetition rate is adjustable. Typically, it is operated in a 1 Hz mode for our experiment in order to achieve time-resolved imaging successfully. A typical pulse energy measured by an energy sensor is 30 mJ and it is focused onto target surface with a lens (of a local length $f = 80$ mm) to a spot diameter of 130 μm. Therefore, the fluence of laser beam is 200 J/cm^2. The target is a polished copper which is mounted on three-dimensional (3D) motion stages. Thus, the spatial location of target can be changed using these stages. The evolution process of laser-induced plasma can be captured by an ICCD camera which is coupled with a microscope tube. The ICCD camera whose gate width is 2 ns is synchronously triggered from the nanosecond laser. Changing the delay time of the exposure time of ICCD camera enable the image to be temporally resolved. In order to obtain the observation process of laser ablation of copper with a RP, the target surface should be ablated by nanosecond laser before

* Corresponding author. Tel.: +86 13718916126.
E-mail address: sbliu@bjut.edu.cn (S.-B. Liu).

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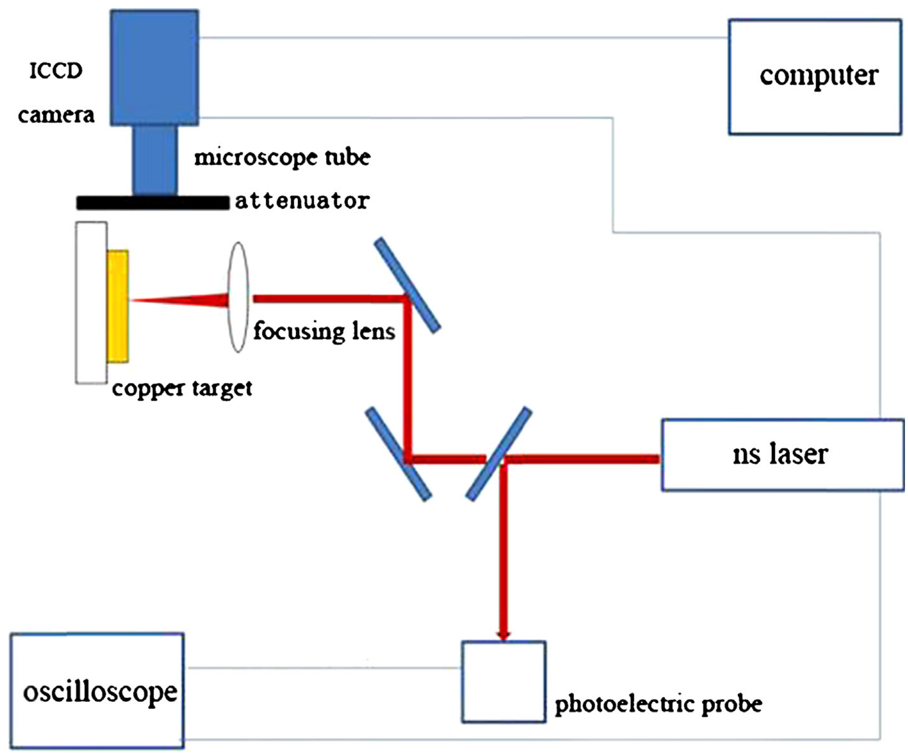

Fig. 1. The experiment setup for time-resolved observation of plasma induced by ns laser pulse.

the experiment is performed. In this study, the RP is prefabricated by only one nanosecond laser pulse. Our experiments are all performed in air.

3. Result and discussion

Fig. 2 shows the time-resolved images of plasma induced by nanosecond laser pulse ablation of copper target with a RP. The laser pulse starts from $t = 0$ ns to $t = 100$ ns, and the target surface is located at the bottom of each image.

When the nanosecond laser pulse arrives at target surface, the copper target will be heated and vaporization will occur with the increase of the energy. Furthermore, the vapor is ionized by laser pulse and plasma is formed. At first, the plasma plume will expand very fast because of its high temperature and high pressure. When the plasma plume is fully developed, it will exist on the target surface until it disappears. Fig. 2 well reflects the above process. We can see that plasma plume appears at the moment of 10 ns from the captured images. Then, the plasma expands very quickly from 10 ns to 50 ns. And the gradually decreasing intensity of radiation after 60 ns means that the plasma plume is decaying.

Based on the time-resolved images, a transient front location of plasma plume as a function of time can be obtained, as is shown in Fig. 3. It can be seen that the plasma front propagates very fast from 10 ns to 20 ns and its velocity gradually slows down with time. At last, the plasma plume stops expanding and dies away. These experimental results are consistent with previous research [4,6].

However, difference between our experimental results and reference [4,6] is also obvious. Firstly, the height of the expanding plasma is more than the experimental results in that reference because the amount of energy absorbed by target with a RP is greater than the flat surface. Moreover, the shock-wave effects occurs during the plasma induced by nanosecond laser expands. While there is no this effects in our experiment resulted from the plasma by non-smooth flat surface. Finally, another interesting phenomenon which is described below has been found in our work.

The gradually reducing intensity of optical emission from plasma showing in Fig. 2 results in blurred image after 60 ns. In order to clearly see the latter process of evolution for laser-induced plasma, a new grayscale palette of equal normalization is applied to the same images (at 60–180 ns) and replotted in Fig. 4.

Fig. 4 presents that the intensity of strongest light emitting area at the top of plasma plume gradually becomes weak. At the same time, we can clearly see that a new bright region above the target surface starts growing significantly and its front begins to expand. In order to figure out this physical process, first of all, we should identify that what the bright region is. Fig. 5 shows the transient front locations of the bright region above the target surface. According to the measurements in Fig. 5, we can calculate that the average velocity of the bright region is around 1.04×10^4 m/s. This value is similar to the previous experimental results [4,6]. On the other hand, its morphology evolution is similar to that of plasma induced by laser ablation of surface target. Hence, based on the above analysis, we can identify that the bright region should be the plasma plume.

However, why does the plasma generate again? We use Fig. 6 which presents the evolution process of plasma to explain this phenomenon. When the non-smooth target surface is exposed by a nanosecond laser pulse, the electrons in target start to absorb the laser energy rapidly and follow on transfer the energy to the ions by electron-lattice colliding [14]. Once the absorbed energy of the electron from laser light is larger than its ionization potential the electrons are stripped from its parent nucleus and jet at speed of v_e out off the target surface. Usually the ionization threshold is far lower than the binding energy of the ions due to the presence of the impurities and defects in the target-materials and therefore only the electrons jet from surface before the absorbed energy by target-ions exceeds the binding energy, such as at the moment t_a during the pulse as shown in Fig. 6. Once the absorbed energy by ions reach the threshold of atom dissociation (such as at t_b) the ions start to escape at speed of v_i from the target surface and start to emit radiation (luminescence) at the roof of the expanding ions because