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Investigation of phase explosion in aluminum induced by nanosecond double pulse technique

Marzieh Akbari Jafarabadi, Mohammad Hossein Mahdieh *

Department of Physics, Iran University of Science and Technology, Narmak, Tehran 13114-16846, Iran

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ABSTRACT

In this paper, the influence of double pulse technique on phase explosion threshold in laser ablation of an aluminum target is investigated. Single and double pulse laser ablation of aluminum target was performed by a high power Nd:YAG laser beam in ambient air. In the double pulse excitation, the two pulses were from a single laser source which separated by a delay time in the range of 5–20 ns. Measuring ablation depth and rate, the phase explosion threshold was estimated in double pulse configuration as well as in the single pulse regime. The results show that in comparison between single and double pulse regimes, the phase explosion threshold fluence is decreased in double pulse configuration. The lowest phase explosion threshold fluence of 0.9 J/cm^2 was obtained at 5 ns delay time. The results also show that plasma shielding effect reduced crater depth at a laser fluence which depended on the laser ablation configuration (single pulse or double pulse). The reduction of crater depth occurs at lower laser fluences for double pulse regime.

1. Introduction

Laser induced ablation has been interested for last decades because of its wide range of applications. Laser micromachining [1], pulsed laser deposition (PLD) [2], nanoparticle production [3], laser material identification [4] and surface nano- texturization [5] are some typical applications of laser ablation.

Laser ablation can be provided by focusing a high power laser beam on a solid target surface. In the process, a portion of the beam energy is absorbed by the free electrons at the target surface. Electron–phonon interaction leads to heat up the target surface. For laser fluences lower than threshold fluence, the interaction of the laser beam and the solid material can only modify the target surface [5]. However, for higher fluences, the surface can be influenced significantly and finally a crater is left on the target surface [1]. The ablation process strongly depends on the laser beam characteristics, target material and the interaction environment. Different processes such as melting, evaporation, plasma formation and phase explosion may occur in the single pulse (SP) laser ablation [1–9]. At sufficiently high laser fluences, a vapor plume which consists of hot plasma electrons and ions, excited and ground-state neutrals can be formed. The hot vapor plume expands into the ambient. In the case of gas or liquid ambient, a shock wave is also formed which moves toward the focusing lens. Due to the reaction force of the material ablation and plasma formation, a shock wave is also formed that propagates inside the target. In the case of long pulse regime (pulse duration > ps), plasma formation and expansion is initiated and continued within the pulse duration time. The hot expanding plasma interacts with the trailing edge of the pulse and absorbs and modifies the laser beam propagation due to plasma shielding effect [7].

Laser ablation can be also performed by multi pulse interacting target surface. The multi pulse laser ablation was first introduced and studied by Piepmeier et al. in 1969 [10]. Their results showed that transfer of energy from plasma to the target surface was responsible for the creation of craters with larger volumes in double pulse (DP) and multi pulse laser ablation. Double pulse technique has been utilized in several arrangements, including different laser beam geometries [10–16], laser wavelengths [11,12], laser pulse durations [13,14] and laser pulse energy proportions [15]. The DP laser ablation, especially DP LIBS[1] has been reviewed by Babushok et al. [16]. The effect of DP laser ablation in different parameters such as plasma temperature, plasma expansion velocity and emission line intensities were overviewed by Babushok et al. The influence of inter-pulse delay time on ion yield, ion kinetic energy,

* Corresponding author. Tel.: +98 21 77240477; fax: +98 21 77240497.
E-mail address: mahdm@iust.ac.ir (M.H. Mahdieh).

[1] Laser induced breakdown spectroscopy.

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crater depth and volume has also been investigated. Double pulse technique was provided using a single laser [10–13,15], and two laser set up [14]. Two beam configurations, i.e. orthogonal [12] and collinear [10,11,13–15] geometries were used for DP laser ablation. In the orthogonal case, the pre pulse is irradiated parallel to the target surface and the main pulse is normally incident to the target surface. Usually the pre pulse is focused at a particular distance above the target surface which can create pre plasma at the target surface. This process usually leads to improve plasma emission and signal enhancement in the relevant applications. In the case of collinear geometry, both pulses are irradiated at similar direction which is orthogonal to the target surface. It must be noted that in both geometries, the second pulse interacts with the plasma as well as the target surface during the irradiation process. The ablation process during DP laser ablation depends on the time scale of the delay time following the pre pulse [11].

Laser induced phase explosion is one of the most important mechanisms of laser ablation, which accompanies with a rise in ablation rate and ejection of micron sized particles from the target surface [17–26]. The theory of phase explosion was first reported by Martynyuk and developed by Kelly et al. [17,18]. However, it was first reported experimentally by Song and Xu in 1998 for irradiating a nickel target by an excimer laser [19]. By using a probe beam deflection method, they showed that large particulates created during the phase explosion, which are responsible for scattering and decreasing the probe beam signal. Thereafter many experimental studies have been carried out and confirmed that phase explosion (explosive boiling) is an important mechanism in nanosecond laser ablation of metal and semiconductor targets [17–26]. In nanosecond laser ablation, target heating is so fast that the target material goes to the metastable region and superheating occurs. Density fluctuations lead to homogeneous nucleation as the target material passes the binode limit (the liquid–vapor equilibrium curve). If the laser fluence is sufficiently high, the molten material may heat up to 0.9 T_c (critical temperature) which is the superheating limit at the atmospheric pressure. As the material surface temperature approaches to the spinode limit, the rate of vapor bubble nucleation increases rapidly. The bubbles with radius bigger than r_c (critical radius in which the bubble is in equilibrium with its surrounding liquid) grows instantaneously and may explode in a mixture of liquid droplets and vapor. Because of the explosive nature of the phenomena, this liquid–vapor phase transition is named phase explosion. Such jumping in the ablation rate and ejection of micron sized particulates in the plume are the two evidences of laser induced phase explosion which were addressed the most by different research groups. By ablation depth measurements, phase explosion was also confirmed for laser ablation of an aluminum target [20]. Shadowgraphy images were also used to visualize the transition from vaporization to phase explosion. Using nanosecond time resolved shadowgraphy technique; it has been shown that phase explosion has a key role in large mass ejection during the ablation process [21]. The threshold fluence for silicon target was also obtained by measuring the crater depth and volume. Recently, we also investigated phase explosion phenomenon in laser ablation of thin aluminum film by a pump–probe technique [25,26]. Measuring the optical transmission and reflection of the probe beam, phase explosion was confirmed for the aluminum target irradiated by a nanosecond Nd:YAG laser. Enhancement of the optical reflectivity of the probe beam from the front surface of the aluminum target was a sign to show that phase explosion occurs.

Since, controlling the ablation rate and crater's size has a key role in all laser ablation applications, a superior knowledge about the dependence of crater characteristics on laser fluence and ablation mechanism is required. To our best knowledge, there is no report to show the influence of pre pulse on phase explosion threshold fluence. In this paper, we investigated the phase explosion phenomena in both SP and DP laser ablation regimes. An aluminum target was irradiated by a high power Q-switched Nd:YAG laser in both SP and DP configurations. The DP regime was provided with a collinear geometry by a single laser. The main pulse was separated in time from the pre pulse in the order of few tens of nanosecond. The two configurations were compared by direct analysis of the residual craters. Three distinct fluence regions were distinguished in both configurations. The delay time between the pre pulse and main pulse affected on the crater's depth trend as well as the phase explosion threshold.

2. The experiment

A schematic diagram of the experimental setup is shown in Fig. 1. The laser beam was provided by a Q-switched Nd:YAG laser with wavelength 1064 nm and ∼10 ns pulse duration. The expanded laser beam was split into two beams by using a beam splitter (S_1 in Fig. 1). In single pulse (SP) configuration, the transmitted beam was blocked and the reflected beam was focused on the target surface by a doublet lens (with 18 cm focal length). In our experiment, collinear configuration was used for double pulse (DP) laser ablation. In DP configuration, the transmitted beam (main pulse) through the splitter was optically delayed with respect to the reflected beam and was focused on the target surface collinear with the reflected beam (pre pulse). The delay time between the pre pulse and main pulse could be changed by varying the distances between three mirrors (M_1, M_2 and M_3 in Fig. 1) at the order of few tens of nanosecond. The energy ratio of the pre pulse and main pulse could be varied and controlled by beam attenuators in the beam path of the main pulse. The energy of the two pulses could be set between 0.4 and 4 mJ/pulse by changing the power supply power. A small fraction of the beam was reflected by a splitter (S_2 in Fig. 1) and the beam energy was measured by a pyroelectric energy meter in each irradiation.

A 5052 aluminum plate (type 5052) with 3 mm thickness was used as the target. The target was polished to have average roughness less than ∼5 μm and was irradiated normally in ambient air. In each irradiation 50 pulses were used to produce a crater. A three dimensional micro-positioner was used for fine adjusting the target surface at the laser beam focal point. The micro-positioner was also used to move the target to a fresh area after each irradiation.

The geometry (depth and width) of each produced crater was characterized by using an optical microscope and image processing

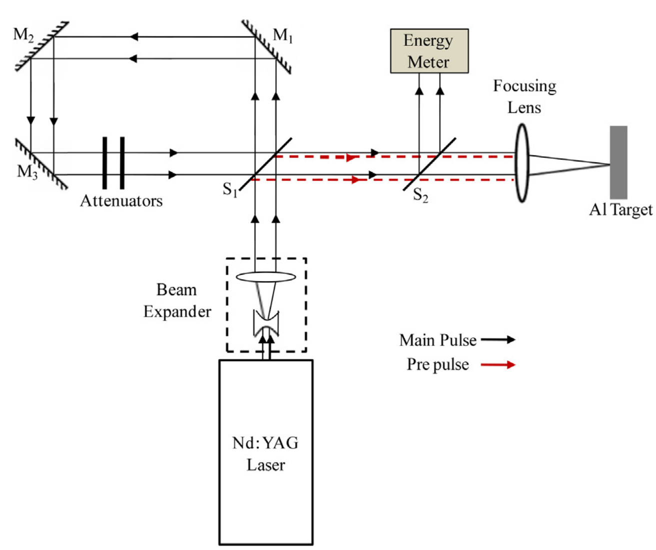

Fig. 1. Schematic diagram of experimental setup.