Spectrochimica Acta Part B 143 (2018) 26–31

Contents lists available at ScienceDirect

Spectrochimica Acta Part B

journal homepage: www.elsevier.com/locate/sab

Nanosecond laser-metal ablation at different ambient conditions

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ARTICLE INFO

Article history:
Received 8 August 2017
Received in revised form 16 February 2018
Accepted 21 February 2018
Available online xxxx

Keywords:
Laser ablation
Metal erosion
Crater profile
Mass ablation
Ambient conditions

ABSTRACT

Ablation of metals under different ambient conditions and laser fluences, was investigated through series of experiments. A 1064 nm, 6 ns Nd:YAG laser was used to ablate 1 mm thick metal targets with laser energy ranging from 2 mJ to 300 mJ. The experiments were designed to study the effect of material properties, laser fluence, ambient gas, and ambient pressure on laser-metal ablation. The first experiment was conducted under vacuum to study the effect of laser fluence and material properties on metal ablation, using a wide range of laser fluences (2 J/cm^2 up to 300 J/cm^2) and two different targets, Al and W. The second experiment was conducted at atmospheric pressure using two different ambient gases air and argon, to understand the effect of ambient gas on laser-metal ablation process. The third experiment was conducted at two different pressures (10 Torr and 760 Torr) using the same ambient gas to investigate the effect of ambient pressure on laser-metal ablation. To compare the different ablation processes, the amount of mass ablated, ablation depth, crater profile and melt formation were measured using White Light Profilometer (WLP). The experimental results show that at low laser fluence: the ablated mass, ablation depth, and height of molten layer follow a logarithmic function of the incident laser fluence. While, at high laser fluence they follow a linear function. This dependence on laser fluence was found to be independent on ambient conditions and irradiated material. The effect of ambient pressure was more pronounced than the effect of ambient gas type. Plasma shielding effect was found to be very pronounced in the presence of ambient gas and led to significant reduction in the total mass ablation.

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1. Introduction

Laser-matter interaction has strongly drawn researchers' attention since the discovery of laser in 1960s. Understanding laser-material interaction is an important topic for deciphering underlying processes as well as for various applications driven by this interaction including medical, industrial, energy, and defense applications. In general, laser ablation is a photo-thermal process in which laser energy gets absorbed in the target. Consequently, this energy heats the target to elevated temperature. This is followed by material removal from the target due to many potential mechanisms namely: vaporization, melt flow, phase explosion and/or normal boiling. Normal boiling requires microseconds to occur which is longer than the pulse duration of nanosecond laser pulse so this phenomenon can be excluded for nanosecond laser ablation [1]. In addition, in nanosecond laser irradiation it was found that, the mass removal due to vaporization mechanism dominates mass removal due to melt flow mechanism [2]. Once the laser intensity gets high enough to heat the target near to the liquid-vapor critical temperature, large density fluctuations occur resulting in the formation of and growth of bubbles inside the liquid, leading to phase explosion [3]. Previous study [2] showed that at high laser fluence, phase explosion is more dominant than vaporization. In summary, the main driving mechanisms for laser ablation are vaporization that occurs at all laser intensities and phase explosion that occurs at high intensity and has a threshold value dependent on liquid-vapor critical temperature. The ablated mass forms plasma plume that propagates in front of the target. This plume forms at early time of the laser pulse and contains free electrons, ions, neutral atoms, and fragments [4]. The remaining part of the incident laser pulse gets absorbed via the free electrons in the plume itself via inverse bremsstrahlung [6]. This results in higher ionization state of the ions, the formation of hot species of ions and electrons [5,7–9], leading to increasing plasma density increase beyond the critical density of the incident laser. Under these conditions, the plasma tends to shield the target preventing the remaining part of the incident laser from interacting with the target, this phenomenon called plasma shielding effect [10]. Furthermore, one of the major effects that must be considered when using long laser pulse duration for ablation is the thermal effect. Thermal effect leads to enduring damage to the target material that results in the formation of molten material around the irradiated spot [11]. Most melting and material removal from the target occurs at early time before plasma density reaches the critical density of the incident laser [12]. This current work shows that, at certain conditions when the ablated plasma is dense enough and confined for relatively long time near to the target surface, radiation from plasma plume can cause material removal as well. Moreover, rapid heating of the target

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https://doi.org/10.1016/j.sab.2018.02.012
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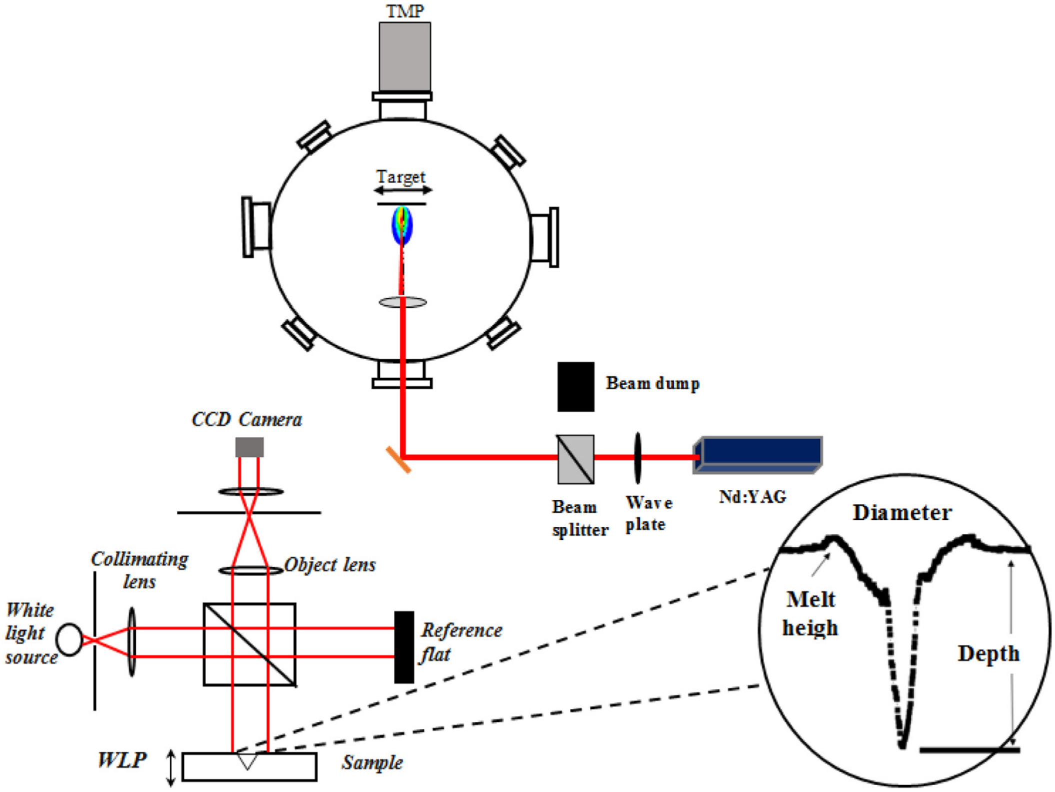

Fig. 1. Experimental setup showing the ablation chamber, laser setup and White Light Profilometer (WLP).

from room temperature to thousands of degrees caused by laser irradiation, was found to alter the optical and thermo-physical properties significantly, such as surface reflectivity, electrical and thermal conductivity, surface tension, latent heat of vaporization [2].

All these mechanisms and processes, when combined, increase the degree of complexity required to model the laser-mater interaction process. Given the complexity of studying laser-material interaction, there are several approaches that have been developed to model the interaction between laser and solid targets including, but not limited to, molecular dynamic (MD) simulation [13], two temperature (TTM) model [11], photo-thermo-hydrodynamic approach [2,14,15]. To the best of our knowledge, the most 3-D comprehensive simulation tool is the HEIGHTS package [16–18] that integrates all various physics of laser-matter interaction. These models vary in the degree of complexity and hence the degree of accuracy based on the physical phenomena that could be included. For validation and benchmarking of such models, experimental data are always needed at different irradiation conditions and for different materials for comprehensive understanding of laser-matter interaction.

In this work, we study the effect of laser fluence, material properties, ambient gas, and ambient pressure on nanosecond laser-metal ablation. The ablated profile was measured using White Light Profilometer (WLP) allowing determination of the ablation depth, the amount of ablated material from targets, and the height of the molten layer around the ablated spot. The findings of this study is of significance for many research including erosion of materials under extreme conditions such as plasma-facing component in magnetic and inertial fusion reactors [19], laser micromachining, metallic etching [20], pulsed laser deposition [21], and fundamental physics.

2. Experimental setup

Ablation of metals under various ambient conditions using a wide range of laser fluences was studied using 6 ns, 1064 nm, Nd:YAG laser.

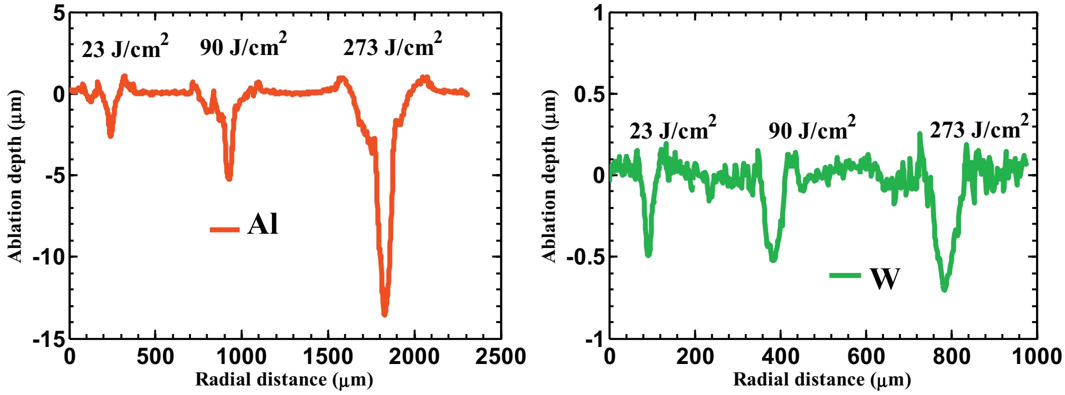

Fig. 2. Ablation profile for Al and W at low, intermediate and high laser fluence from a single laser pulse.

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