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Experimental study of laser-induced plasma: Influence of laser fluence and pulse duration

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ABSTRACT

Influence of laser fluence and pulse duration on the morphology and the internal structure of plasma induced by infrared nanosecond laser pulse on an aluminum target placed in an argon ambient gas of one atmosphere pressure was experimentally studied. Dual-wavelength differential spectroscopic imaging was used in the experiment, which allowed observing the detailed structure inside of the ablation plume with distributions of species evaporated from the target as well as contributed by the ambient gas. Different regimes of post-ablation interaction were investigated using different laser fluences and pulse durations. We demonstrate in particular that plasma shielding due to various species localized in different zones inside of the plume leads to different morphologies and internal structures of the plasma. At moderate fluence, the plasma shielding due to the ablation vapor localized in the central part of the plume leads to its nearly spherical expansion with a layered structure of the distribution of different species. At higher fluence, the plasma shielding becomes strongly contributed by ionized ambient gas localized in the propagation front of the plume. An elongated morphology of the plume is observed with a zone of mixing between different species evaporated from the target or contributed by the ambient gas. Finally with extremely strong plasma shielding by ionized ambient gas in the case of a long duration pulse at high fluence, a delayed evaporation from the target is observed due to the ejection of melted material by splashing.

1. Introduction

It is well known that laser-induced plasma, as a spectroscopic emission source, exhibits transient behavior [1]. Time-resolved and gated detection can greatly improve the performance of laser-induced breakdown spectroscopy (LIBS) especially that of calibration-free LIBS (CF-LIBS) with a better determination of plasma temperature [2]. The temporal evolution of the plasma is however correlated to its morphology and its spatial inhomogeneity [3]. The determination of the morphology as well as the internal structure of the plasma together with their evolution during plasma expansion into the ambient gas is therefore crucial for optimization of the use of the plasma as spectroscopic emission source. Early considerations on the morphology of laser-induced plasma are mainly based on the hydrodynamic description of the plasma propagation, often referred to as Sedov point-blast model or piston model [4,5]. In such model, the energy of the incident laser pulse is considered to be instantaneously and punctually deposited on the target surface. Evolutions of the morphology and the internal structure of the ablation plume are considered as the consequence of its hydrodynamic expansion into the ambient gas. Recent works showed experimental evidences of the importance of post-ablation interaction between the tailing part of the laser pulse and the ablation plume in the determination of its morphology [6–11]. Especially different regimes of laser-supported absorption wave (LSAW), such as laser-supported combustion (LSC) wave and laser-supported detonation (LSD) wave [12], have been identified correlating to different observed plasma morphologies. Not only the strength but also the spatial localization of the absorption in the plume influences the plasma morphology [6]. The morphology and the internal structure of the plasma are therefore directly related to the phenomenon of plasma shielding which has been extensively studied for its influence on laser ablation and on the optical emission property of the generated plasma [13–16].

In this paper, we study the influence of laser fluence and pulse duration on the morphology and the internal structure of plasma induced by infrared (IR) nanosecond (ns) laser pulse on an aluminum target placed in an argon ambient gas of one atmosphere pressure. Such study was carried out for different configurations of plasma shielding due to the use of pulses with different energies and durations. Specific plasma morphologies and internal structures will be reported in the different interaction regimes. Plasma morphology and structure observed after the end of the laser pulse showed characteristic features which will be used to infer the dominant mechanism of plasma shielding in terms of laser-supported absorption

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waves. LSC wave is thus considered as the dominant process of post-ablation interaction for ablation with moderate laser fluence, while LSD wave dominates the early stage propagation behavior of the plasma induced by higher fluence laser pulse. Dual-wavelength differential spectroscopic imaging technique was used in this experiment, which allowed the detailed internal structure of the plasma being observed in two dimensions with the distributions in the plume of the species evaporated from the target as well as contributed by the ambient gas.

2. Experimental setup and data treatment

2.1. Experimental setup

The experimental setup is shown in Fig. 1. Two Nd:YAG lasers operated at a repetition rate of 10 Hz and at the fundamental wavelength of 1064 nm were used to deliver pulses with two different pulse durations. They were respectively provided by Quantel laser company (Brilliant) and CILAS laser company. For simplicity, we name them respectively laser "B" for Brilliant laser and laser "C" for CILAS laser in this paper. Laser B was used with two pulse energies (measured before hitting the target) of 20 mJ and 50 mJ with a nominal pulse duration of 4 ns (FWHM). Laser C was used with a pulse energy of 50 mJ. Its pulse duration was measured at 25 ns (FWHM). Because the initial beam diameters were different for these two lasers, a telescope consisting of two lenses, L1 (divergent) and L2 (convergent), was used to magnify the beam diameter of laser C to fit that of laser B of 6 mm. The paths of the two lasers were then superimposed by using two high reflection mirrors, M1 and M2. The later could be removed to let the beam of laser B pass through for alternative use of the two lasers. The pulse energy delivered to the target was precisely controlled by using an ensemble of a half-wave plate (HWP) and a Glan prism (GP). A mechanical beam shutter (BSH) was used to control the delivery of burst of pulses to the target. A beam splitter (BS) sampled each delivered pulse by sending 4% of it to a photodiode (PD), which generated a synchronization signal to trigger the detection system. A personal computer (PC) was used to ensure the synchronization of the different parts in the experiment and to control the measurement procedure.

Laser pulses were focused onto the target by a lens (L3) with a focal length of 50 mm. The focus point of the beams was set under the target surface with a shift of about 1.5 mm in order to avoid direct breakdown in the ambient gas for the used laser pulse energies. The target, a piece of pure aluminum (99.99%) was polished and cleaned prior to the ablation. During a measurement, the target was translated using a motorized X–Y stage to provide a fresh surface to each burst of laser pulses. The distance between the focusing lens (L3) and the target surface was maintained constant during the measurement with the help of a monitoring system which consisted of a combination of a laser pointer (not shown in Fig. 1) with its beam in oblique incidence onto the target surface and a video camera (C) installed above the mirror M3. The diameter of the laser beam spot on the surface of the target was estimated by measuring the size of the craters using a microscope to be about 200 μm for the both lasers. Microscopic images of the craters were also used to ensure that the laser beams was in normal incidence on the target surface. The fluence delivered to the target (theoretically reachable if not absorbed) was thus determined at 65 J/cm^2 for a pulse energy of 20 mJ and 160 J/cm^2 for a pulse energy of 50 mJ. A flow of argon gas was delivered by a pair of tubes installed above the target and surrounding the laser impact zone, with a fixed rate of 8 l/min. Such flow ensured the expansion of the plasma into a pure argon environment at one atmosphere pressure. A 4-f system consisting of two quartz lenses (L4 and L5 in Fig. 1) with focal lengths respectively of 7.5 and 20 cm was used to form a magnified image of the produced plasma. The image was directly recorded by an intensified charge coupled device (ICCD) camera (iStar from Andor Technology) placed at the image plane. The spatial resolution of the camera was determined with a ruler illuminated by visible light to be 5 μm per pixel for a wavelength around 500 nm. A narrowband filter (F in Fig. 1) was inserted between the two lenses of the 4-f system in order to take an image of the plasma with the emission in the bandwidth selected by the filter. Since the emission from the plasma detected by the ICCD camera extended from the near ultraviolet (UV) to the near infrared (IR), chromatic variation of the focal distances of the lenses introduced a variation of the magnification of the imaging system as a function of the wavelength selected to image the plasma. Such variation was corrected in our experiment by applying a correction factor to raw images.

2.2. Experimental protocol and data treatment

In our experiment, two-dimensional distributions of the intensities emitted by 4 species in the plasma were observed with the help of the imaging system described above. These 4 species corresponded to neutral and singly ionized aluminum (Al I and Al II) and neutral and singly ionized argon (Ar I and Ar II). The choice of the simple configuration of a pure aluminum target in argon ambient gas allowed the representation of the plasma with these 4 species. An emission spectrum from the plasma was first recorded by focusing a pulse of 50 mJ from laser B and by collecting the emission from the generated plasma with an optical fiber placed in the image plane of the 4-f

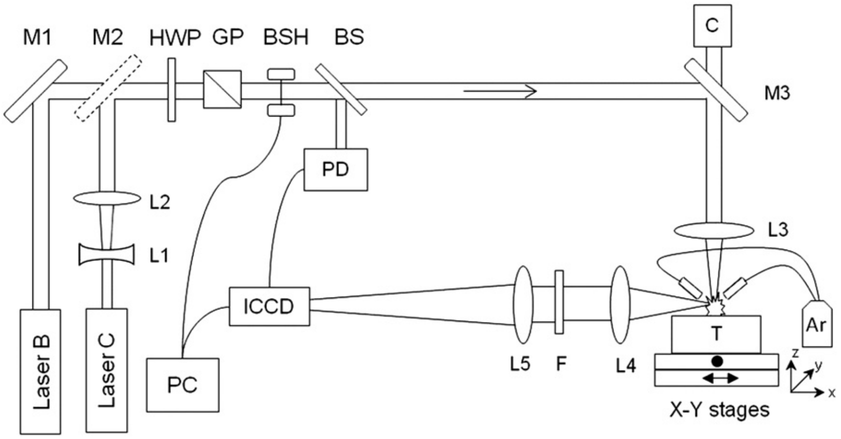

Fig. 1. Schematic presentation of the experimental setup. M1–M3: mirrors, L1–L5: lenses, HWP: half-wave plate, GP: Glan prism, BSH: beam shutter, BS: beam splitter, C: camera, T: target, F: narrowband filter, PD: photodiode, PC: computer.