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Influence of vacuum on nanosecond laser-induced surface damage morphology in fused silica at 1064 nm

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ABSTRACT

The influence of vacuum on nanosecond laser-induced damage at the exit surface of fused silica components is investigated at 1064 nm. In the present study, as previously observed in air, ring patterns surrounding laser-induced damage sites are systematically observed on a plane surface when initiated by multiple longitudinal modes laser pulses. Compared to air, the printed pattern is clearly more concentrated. The obtained correlation between the damage morphology and the temporal structure of the pulses suggests a laser-driven ablation mechanism resulting in a thorough imprint of energy deposit. The ablation process is assumed to be subsequent to an activation of the surface by hot electrons related to the diffusive expansion of a plasma formed from silica. This interpretation is strongly reinforced with additional experiments performed on an optical grating in vacuum on which damage sites do not show any ring pattern. Qualitatively, in vacuum, the intensity-dependent ring appearance speed $V \propto I^{1/2}$ is shown to be different than in air where $V \propto I^{1/3}$. This demonstrates that the mechanisms of formation of ring patterns are different in vacuum than in air. Moreover, the mechanism responsible of the propagation of the activation front in vacuum is shown to be outdone when experiments are performed in air.

1. Introduction

Laser-dielectric interaction in vacuum environments has been investigated for several years [1,2]. The observed differences of nanosecond laser-induced damage (LID) between atmospheric and vacuum environments have been studied [3–6]. In this context, LID in fused silica remains a major issue, since it is one of the most widely used optical materials. In the past decades, LID at surfaces of transparent dielectrics has been shown to arise from subsurface defects absorbing the incident laser flux [7]. This interaction results in a surface plasma leading to the formation of a damage site [8]. More recently, studies performed in air environment have shown the growing interest in working with Multiple Longitudinal Modes (MLM) pulses [9–11]. This kind of pulses correlated to the damage morphology can provide a powerful tool to access the chronology of the damage mechanisms from incubation to expansion in the near infrared domain [12,13]. Therefore, we propose to transpose this experimental study so as to investigate LID formation in vacuum environment.

In the present work, ring patterns are systematically observed on damage sites initiated with single MLM pulses at 1064 nm in vacuum on plane surfaces. The removal of material due to an ablation process is subsequent to the activation of the silica surface provided by the diffusive expansion of the plasma at the vicinity of the surface. This hypothesis is confronted to additional experiments performed in vacuum on an optical grating etched in fused silica in order to study the influence of the surface state. The periodical structure of the grating is shown to inhibit the expansion of this plasma; this suggests that the expansion process likely takes place along the sample surface. A model based on a diffusive process related with thermal conduction is thus proposed to interpret such behavior. As a conclusion, a direct comparison is made between LID formation in air and vacuum environments so as to emphasize the differences between the mechanisms responsible for the ring patterns formation. Thanks to our analysis, the estimation of the diameter of a damage site is possible for both environments with the knowledge of the fluence that feeds the mechanism of expansion of the ring pattern.

2. Experimental investigations of the influence of vacuum on LID morphologies

The laser facility described in Ref. [14] is used at 1064 nm both in Single Longitudinal Mode (SLM) and MLM regimes to perform this

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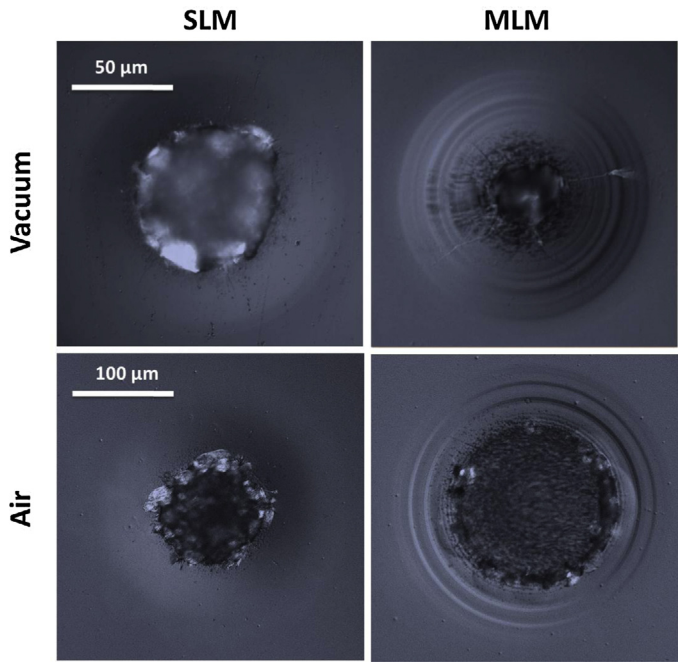

Fig. 1. NIC images of typical damage sites obtained in air and vacuum environments for both SLM and MLM configurations. The fluence of the four shots is 110 J/cm^2. The scale of the images in vacuum is twice smaller than the scale of the images in air.

study. In the SLM regime, the pulse equivalent duration, defined as the ratio of the energy over the peak power, is 9 ns. The sample is positioned in the focal plane where the spot is Gaussian-shaped and 1 mm in diameter at 1/e. The Rayleigh range of the beam is much longer than the sample thickness. In the MLM regime, the random spectral fluctuations induced by longitudinal mode beating in the laser cavity result in a strong variation of the positions and magnitudes of the spikes in the intensity profiles from pulse to pulse. Therefore, the intensity profiles are recorded for each laser shot with a 25 GHz bandwidth photodiode and a 33 GHz bandwidth oscilloscope (Tektronix DSA73304D). Experiments are performed on fused silica samples of 10 mm thickness that exhibit plane superpolished surfaces. The samples are used as a window for the vacuum chamber in which the test will be performed. The front surface is in air environment whereas the rear surface is in vacuum environment. A turbo-molecular pump permits to reach a pressure level of 10^{-5} mbar. Each damage site was initiated by a single laser pulse at 1064 nm. Since the beam is collimated during the propagation in the sample, LID systematically occurs on the rear surface. All samples are illuminated during the first hour of their exposition to vacuum even though it might not play a role in our single shot experiments. For both SLM and MLM regimes, the largest damage sites show very similar sizes despite strongly different morphologies. Nomarski Interference Contrast (NIC) micrographs of these damage sites obtained in vacuum are shown in Fig. 1, together with equivalent damage achieved in air environment. The fluences of the shots that initiated the damage sites are 110 J/cm^2 in all cases. In both SLM and MLM configurations, the damage sizes are reduced by more than a factor of two once the surrounding air is removed. Thus, the scales are multiplied by a factor of two between the images in air and in vacuum. These observations suggest that the environment strongly influences the damage expansion speed. Moreover, the presence of a ring pattern is again systematically obtained in the MLM configuration in vacuum environment.

Each ring pattern observed on damage sites in the case of MLM pulses is closely associated with intensity spikes. As in air environment, we match space and time scales thereby making possible the evaluation of ring appearance speed [12]. In Fig. 2, a damage site obtained in vacuum environment is shown with the associated intensity profile of the MLM pulse. The white dashed arrows exhibit the correspondence between spikes and rings showing that inner rings appear before outer ones. The red arrow indicates the time t_0 (set to zero on the time scale), associated to the beginning of the formation of the rings. The time t_0 is unique by definition and cannot be shifted to another peak. The dilatation as well as the matching of the temporal profile with the rings is also unique. This matching allows us to precisely define the instantaneous ring appearance speed as the ratio of the distance between two successive rings to the time interval separating the two adjacent temporal spikes. Although most intensity spikes can be matched with rings, some dispersion in speed measurement is observed, meaning that ring appearance speed is not constant throughout the pulse. For each speed measurement, we calculate the short-time-average intensity which corresponds to the averaged intensity over the time between the two adjacent spikes (e.g. white dashed arrows in Fig. 2) used to calculate the ring appearance speed.

As an example, we have reported in Fig. 3 the ring appearance speed V as a function of short-time-average laser intensity I for three damage sites. The three sites in Fig. 3 show very similar

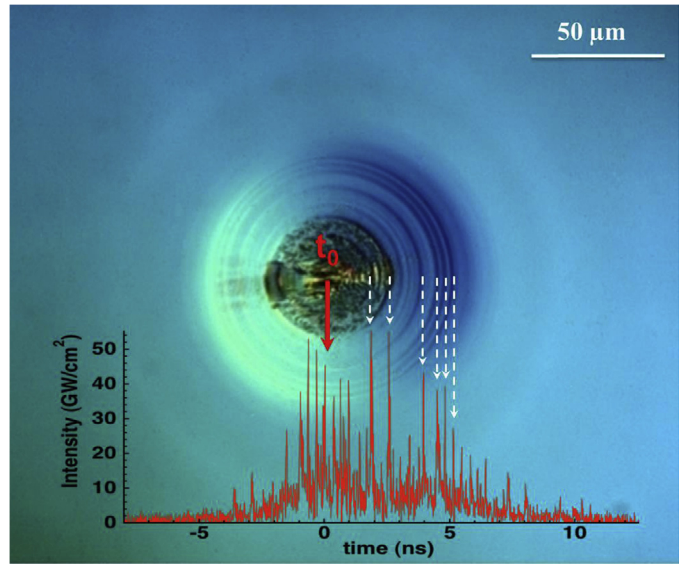

Fig. 2. Correlation between the morphology of a damage site initiated at the rear surface of a fused silica sample in vacuum and the temporal profile of the corresponding MLM pulse.

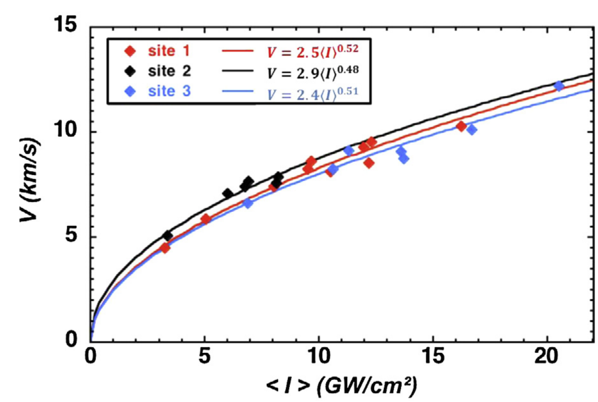

Fig. 3. Instantaneous ring appearance speed as a function of short-time-average laser intensity for three sites initiated in vacuum by three different MLM pulses. The curves stand for the fits of corresponding data.