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Experimental study on 800 nm femtosecond laser ablation of fused silica in air and vacuum

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ABSTRACT

Ablation rates of fused silica were studied as a function of femtosecond laser pulse fluences (0.7–41 J/cm^2) in air and vacuum. The experiment was conducted by using a Ti:sapphire laser that emits radiation at 800 nm with a pulse width of 35 fs and a repetition rate of 10 Hz. The morphology and ablation depth of laser-induced damage crater were evaluated by using optical microscopy and scanning electron microscopy (SEM). Ablation rates were calculated from the depth of craters induced by multiple laser pulses. Results showed that two ablation regimes, i.e. non-thermal and thermal ablation co-existed in air and vacuum at low and moderate fluences. A drop of ablation rate was observed at high fluence (higher than 9.5 J/cm^2) in air. While in vacuum, the ablation rate increased continuously with the increasing of laser fluence and much higher than that in air. The drop of ablation rate observed at high fluence in air was due to the strong defocusing effects associated with the non-equilibrium ionization of air. Furthermore, the laser-induced damage threshold (LIDT), which was determined from the relationship between crater area and the logarithm of laser energy, was found to depend on the number of incident pulses on the same spot, and similar phenomenon was observed in air and vacuum.

1. Introduction

Femtosecond laser ablation and laser induced damage are studied extensively in dielectrics [1,2], metals [3–6], and semiconductors [2,7], due to the great importance and interest in micro- and submicro-machining and processing [8–11]. The laser ablation efficiency, morphology, quality, and ablation mechanisms depend on laser parameters (e.g. pulses duration [3], pulse-trains [10,11], wavelength [9], and fluence etc.), material properties [2], and environment (e.g. air, pressure or vacuum) [5,6]. The ablation mechanisms [12–15] include laser energy deposition processes and material remove processes, such as thermal evaporation, coulomb explosion [13], spallation, critical-point phase separation, phase explosion, and fragmentation [14] etc.

The ablation mechanisms are important to the ablation morphology, which will further influence micromachining efficiency and quality. A transition between non-thermal and thermal ablation of metals have been widely investigated depending on the magnitude of fluence in past few decades [2–6]. In the low fluence regime, the ablation rate is related to the optical penetration depth; while in the high fluence regime, the ablation rate is influenced by thermal diffusion length [2–4]. Comparing to the metals, the dielectrics are almost transparent to the near-infrared femtosecond laser. The electrons are excited to conduction band by nonlinear absorption through multiphoton ionization and impact ionization [16–18]. The conduction band electrons (CBEs) absorb laser energy, and then laser induced damage and material ablation will be observed. The non-thermal and thermal ablation also exist in fused silica ablation, which relates to the pulse duration, wavelength and pulse intensity [2,9,12,19].

Another important factor influencing material ablation is environment (e.g. air, vacuum, or pressure) [1,2,4–6,20]. Especially in high fluence regime, the laser-induced air breakdown, or laser-plasma interaction affects the energy deposition in material, and the ablation rate increases [3,4] or even decreases [1] with the increasing of laser fluence. However, few researches about the ablation rate of fused silica in high fluence regime in vacuum are reported. In this article, the ablation rates of fused silica were compared in vacuum and air over a wide range of laser fluence regimes. The dependence of laser-induced damage threshold (LIDT) on pulse number was investigated. The accumulated damage effect,

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associated with incubation processes, and the ablation mechanisms were explored.

2. Experiment

Fused silica samples (JGS1) with a dimension of 15 mm × 15 mm × 1 mm and roughness less than 1 nm rms were used as substrates. Experiments were performed in air and vacuum (1.2×10^{-3} Pa). A commercial chirped-pulse-amplification (CPA) Ti:sapphire laser system (spectra physics) was used to generate a linearly polarized laser pulse, with a pulse duration of 35 fs at a central wavelength of 800 nm. The system delivered a maximum energy of 4.3 mJ/pulse (A beam splitter was used to split a beam with energy up to 1.6 mJ/pulse to ablate samples). A repetition rate of 10 Hz was used in all experiments. A neutral density filter was functioned as the energy attenuator to adjust the laser energy. An energy detector was used to measure the pulse energy of a split-off portion of the beam. The pulses were focused by a 150-mm-focal-length lens onto the surface of samples. The samples were mounted on a motorized *x* and *y* transition stage. The number of pulses striking the target was controlled by a commercial electronic shutter (GCI-73M, Daheng Optics Inc.). Craters with variable depth were created by using multiple laser pulses, varying from 10 to 100 pulses. The ablation depth of the crater was characterized by using a Nikon E600W polarizing optical light microscope with magnifications of 20× and 50×. The morphology of ablation crater was examined by using optical microscope and scanning electron microscope (SEM, Phenom Pure).

3. Results and discussion

Due to the Gaussian energy distribution, the relationship between the laser-induced crater area, *S*, and laser fluence, *F*, is given by Eq. (1) [17,21]:

$$S = \frac{\pi}{2} w_0^2 \ln\left(\frac{F}{F_{th}}\right) \quad (1)$$

where F_{th} is the laser-induced damage threshold (LIDT) fluence. Fig. 1 shows the measured crater area, *S*, versus the pulse energy, *E*, with various pulse numbers irradiated on the same spot. Laser fluence is proportional to the laser energy. By extrapolating the regression line to $S = 0$, we can obtain the damage threshold fluences F_{th}, which are shown in Fig. 2. The laser beam spot radius (ω_0) focused on the fused silica surface is deduced to 43 ± 2 μm calculating from Eq. (1). The relative error of LIDT determination is estimated as 10%, which may due to the evaluation of the crater size and the fluctuation of laser energy. For a single pulse, the F_{th} is 2.1 ± 0.2 J/cm^2. Similar experimental threshold fluences of fused silica were reported under 800 nm fs laser pulse damage [17,22,23].

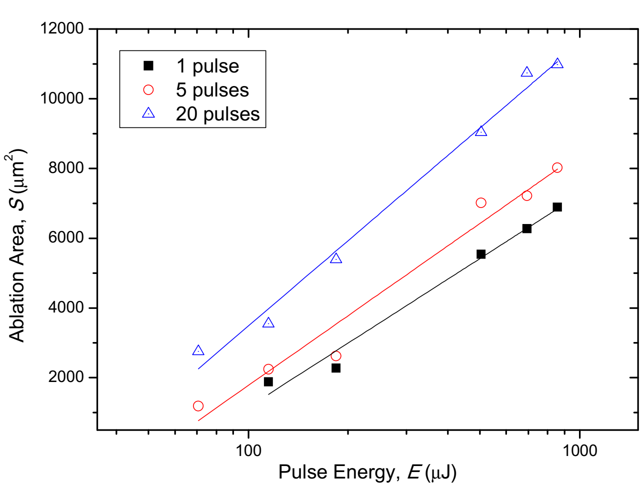

Fig. 1. Ablation crater area, *S*, vs laser pulse energy, *E*, in air. Ablation area and the logarithm of pulse energy is in a linear relationship.

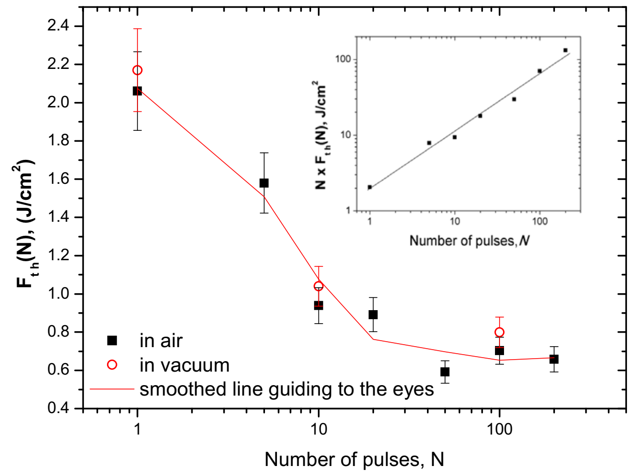

Fig. 2. The dependence of laser induced damage threshold (LIDT), $F_{th}(N)$, on pulse number, *N*. The solid line in inset figure shows a fit according to Eq. (2), yield $\gamma = 0.76$.

As shown in Fig. 2, the ablation threshold fluence decreases with the number of applied laser pulses per site. Similar accumulative behavior under ultra-short laser pulse illumination was observed in different types of materials, e.g. metals [2], semiconductors [24], fused silica [2,23], and polymers [25]. The incubation phenomena can be expressed by Eq. (2) [26]:

$$F_{th}(N) = F_{th}(1) \times N^{(\gamma-1)} \quad (2)$$

where $F_{th}(N)$ is the threshold fluence for different number of pulses (*N*). The exponent γ is characterized as the degree of incubation in the material. For $\gamma = 1$, the threshold fluence is not dependent on the number of pulses. According to Eq. (2), the logarithm of the product ($N \times F_{th}(N)$) is proportional to log(*N*) with a proportionality coefficient γ. As shown in the inset of Fig. 2, the fitted γ is 0.76. The result is similar to that of InP ablation reported in Ref. [24], and shows a significant influence of accumulation effects. For example, the ablation threshold fluence for $N = 100$ laser pulses is approximately 34% of the single-pulse value. The fs laser-induced defects in fused silica may decrease the LIDT of the multiple pulses [27]. Interestingly, as shown in Fig. 2, almost no difference of LIDT on fused silica surface was observed in air and vacuum condition.

Significant physical information and ablation mechanism can be obtained from the studies of the crater depths and ablation rates [1–6,28]. Fig. 3(a) shows the typical phenomena of fused silica ablation in air. The crater depth increases linearly with the number of pulses from 10 to 100. Here, the ablation fluences are 2.5, 4.6, 9.4 and 14.1 J/cm^2, respectively. The average ablation rate was gained by fitting the linear coefficient between the crater depth and the number of pulses. The dependence of ablation rates on the logarithm laser fluence was plotted in Fig. 3(b). There are three regimes in Fig. 3(b). In the low laser fluence regime (<4.5 J/cm^2), the ablation rate gradually increases up to 300 nm/pulse; In the moderate fluence regime (4.5–9.5 J/cm^2), the ablation rate increases from about 300 nm/pulse to 900 nm/pulse at a faster speed; While in the high fluence regime (>9.5 J/cm^2), the ablation rate decreases with the increasing of laser fluence. The decreasing of ablation rate may due to the strong defocusing effects associated with the non-equilibrium ionization of air [1].