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Single-shot laser-induced damage threshold of free-standing nanometer-thin diamond-like carbon foils

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ABSTRACT

Single-shot laser-induced damage threshold (LIDT) of free-standing nanometer-thin diamond-like carbon (DLC) foils was measured in vacuum environment for pulse durations from 50 fs to 200 ps. It is found that, due to higher surface defects density, the LIDT of free-standing ultrathin DLC foils is lower than that of bulk DLC by a factor of 3, and the damage fluence is almost a constant of about 0.1 J/cm^2 when the pulse duration is longer than 500 fs. Different from DLC films coated on silicon wafer, the damage fluence of free-standing DLC has a weak dependence on their thickness. Based on the measurement, the damage mechanism is illustrated by virtue of the carrier population analysis, and the requirement on the temporal laser contrast when DLC targets are used in relativistic laser-plasma experiment is discussed.

1. Introduction

Interaction of ultrahigh-intensity laser pulses with ultrathin foils recently becomes a very attractive topic in laser-plasma research. It has been demonstrated that energetic protons up to tens of MeV [1–3] and coherent extreme ultraviolet/X-ray [4–8] emission can be generated from such interaction at relativistic laser intensity ($I > 10^{18}$ W/cm^2), which may lead to table-top particle/radiation source for many applications [9,10]. For all of the experiments at such intensity, the laser-induced damage threshold (LIDT) of the targets is a crucial parameter that can significantly influence the results, as the targets must survive through the prepulse before interacting with the main pulse. Many kinds of free-standing ultrathin foils made of different materials have been exploited in experiments as targets but detailed studies on their LIDT were rarely seen. Usually it was assumed that the LIDTs of the thin foils are the same as the bulk materials.

However, there are several reasons disproving the reckless use of bulk material's LIDT for ultrathin foils in relativistic laser plasma experiments: (1) The thicknesses of the foils sometimes are only a few nanometers, which is already close to the skin depth of the materials and will impose significant influence on the laser absorption and heat dissipation process. (2) The optical properties of ultrathin free-standing foils in general are different from that of the corresponding bulk materials due to the existence of surface defects and internal stress. (3) Most LIDT measurements in literatures are performed in air with multiple shots, so defect incubation and fatigue effects are included. But the thin foil targets in relativistic laser plasma experiments are shot by single pulses in vacuum. Because of these reasons, the single-shot LIDT of free-standing ultrathin foils in vacuum environment needs to be specifically studied.

In this letter, we report on the experimental results of the single-shot LIDT of free-standing diamond-like carbon (DLC) foils measured in vacuum environment. The dependence of LIDT on the laser pulse duration and on the thickness of the foils is revealed. It is found that the LIDT of ultrathin DLC foil is lower than that of bulk DLC and weakly depends on the thickness. The damage fluence is almost a constant when the pulse duration is longer than 500 fs. Based on the measurements, the damage mechanism is illustrated by virtue of the carrier population analysis.

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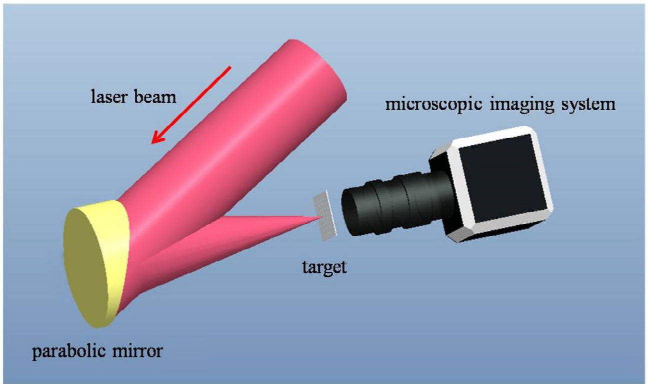

Fig. 1. Schematic configuration of experiments.

2. Experimental setup and methods

In order to obtain the single-shot LDT of the foils under the environment as in laser plasma experiments, we developed a method to perform the measurement at the shooting position in the vacuum chamber. The experiments were carried out by using the ATLAS Ti: Sapphire laser facility at the Max-Planck-Institut für Quantum Optik. The laser beam, target chamber, and target imaging system were the same as in relativistic laser plasma experiments (Fig. 1). The targets were precisely positioned at the focus spot with high-precision linear stages and shot by the laser pulses with different intensity and durations. After each shot, the target was front-illuminated by a collimated light source, and imaged by a 12 bit charged coupled device (CCD) behind a long-working-distance microscope objective lens to check the damage caused by the pulse. After saving the image of the shot target, a fresh target was moved in for the next shot to avoid multi-pulse effects. The full width of half maximum (FWHM) diameter of the focus spot was 15 μm, which was measured by the same microscopic imaging system as that for target imaging. The pulse duration was adjusted from 50 fs to 200 ps by changing the group delay dispersion (GDD) of the pulses. A FROG system (Swamp Optics) and a second-order auto correlator were used to measure the pulse duration. The pulse energy was varied by using different neutral density optical filters before the compressor. All the filters were thinner than 2 mm to avoid the self-phase modulation and pulse front distortion. A pyroelectric detector PE50 (OPHIR) was used to measure the pulse energy and calibrate the filters. The measured rms of the energy variation was less than 2%.

Free-standing DLC foils with thickness of 5 nm, 20 nm and 40 nm were used as targets. They were fabricated by filtered cathodic vacuum arc deposition (FCVAD) on NaCl layer and floated on a holder with 500 μm pinhole [11] as free-standing targets. The ratio of sp^3 bonds in such DLC foils was about 85%. Because of the high sp^3 bonds level, they have wide band gap up to 3.5 eV [12], high strength [13] and inert chemical properties. In previous studies, it has been found that they normally outperform many other targets like amorphous graphite and plastic foils in relativistic laser plasma experiments. Fig. 2 shows the morphology of 40 nm DLC targets after shooting by 50 fs laser pulses at different intensity, and the intensity distribution around the focus spot. At the peak intensity of

1.2×10^{12} W/cm^2 (Fig. 2(a)), the laser pulse didn't induce distinguishable damage on the foil. The foil was intact. At the peak intensity of 4.2×10^{12} W/cm^2 (Fig. 2(b)), a small pinhole with diameter of 18 μm was found on the foil. So the foil was already damaged at that intensity. The edge of the pinhole turned to dark due to the graphitization of DLC. With the increase of laser intensity, the damaged area increased in size as well. At the intensity of 1.3×10^{13} W/cm^2(Fig. 2(c)), the average diameter of the hole had increased to 36.5 μm. It should be noticed that the damaged area of the targets had the shape highly similar to the intensity distributions of the laser pulses. This indicates that the damage was intensity-determined, and lateral thermal damage was neglectable.

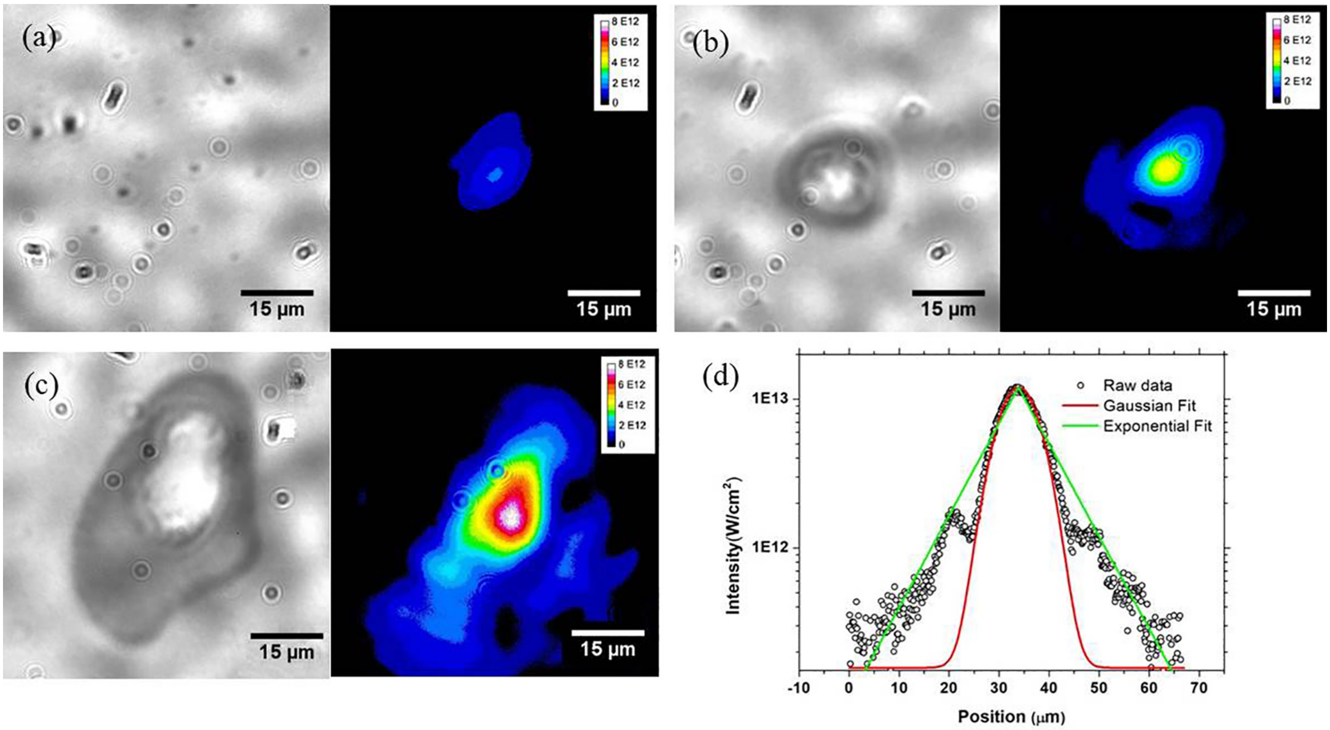

Fig. 2. Damage morphology of DLC targets (left panel) and corresponding intensity distribution of the laser pulses (right panel) at the intensity of 1.2×10^{12} W/cm^2 (a), 4.2×10^{12} W/cm^2 (b) and 1.1×10^{13} W/cm^2 (c). (d) A line-out of the intensity distribution (scattered black circle) around the focus spot. The distribution is Gaussian with $\sigma_{FWHM} = 14.6\ \mu$m nearby the focus spot. Far away from the focus spot, the intensity distribution can be fitted by $I = I_0 \exp(-x/7.5\ \mu\text{m})$.