CHIN. PHYS. LETT. Vol. 26, No. 1 (2009) 017901

Laser-Induced Damage Growth on Larger-Aperture Fused Silica Optical Components at 351 nm

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(Received 21 October 2008)

Laser-induced damage is a key lifetime limiter for optics in high-power laser facility. Damage initiation and growth under 351 nm high-fluence laser irradiation are observed on larger-aperture fused silica optics. The input surface of one fused silica component is damaged most severely and an explanation is presented. Obscurations and the area of a scratch on it are found to grow exponentially with the shot number. The area of damage site grows linearly. Micrographs of damage sites support the micro-explosion damage model which could be used to qualitatively explain the phenomena.

PACS: 79. 20. Ds, 42. 70. Ce, 61. 72. J–

In the context of large high-power laser facilities, the lifetime of optical components is a major concern.[1,2] A main cause of lifetime reduction is laser-induced damage. It is believed that material imperfections, self-focusing and contaminations are the causes of the damage, especially surface damage.[3] More worrisomely, the initial damage would grow rapidly with repetitive pulses.[4] Many studies were carried out to understand the process of damage initiation and growth. However, most damage experiments were conducted off-line at small-aperture and low energy platforms. Due to the aperture-effect, the difference could strongly affect the damage performance.[5] Therefore we made the first attempt to carry out an on-line experiment on a high-power laser facility to obtain the damage performance of large-aperture fused silica optical components at 351 nm laser irradiation. In this Letter, we present the experiment results.

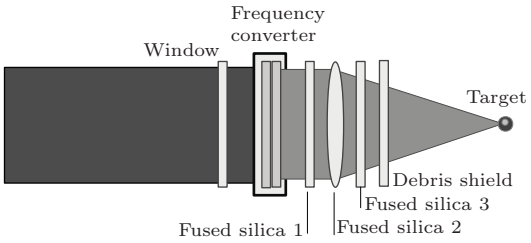


Fig. 1. Schematic of the optical layout configuration of the FOA.

Main specifications of the experiment laser facility are listed as follow: beam size $29 \times 29\,\mathrm{cm}^2$, wavelength 0.351 μm, output energy 1.0 kJ/0.35 μm/1.0 ns/beam, 1.6 kJ/0.35 μm/3.0 ns/beam, pulse durations 1.0 ns and 3.0 ns (square pulse)

During every shot, the laser light amplified by the boost and main amplifier was delivered into the final optical assembly (FOA) which consists of a window, a frequency converter, and three fused silica components of different functions. The schematic of the optical layout configuration of the FOA is shown in Fig. 1. By passing through the frequency converter the wavelength of the laser light changed from 1053 nm to 351 nm. The third harmonic generation (THG) efficiency was maintained high in the high-fluence operating phase, as shown by the solid curve in Fig. 2. Thus we could reasonably assume that the fused silica components mainly bear the 351 nm light.

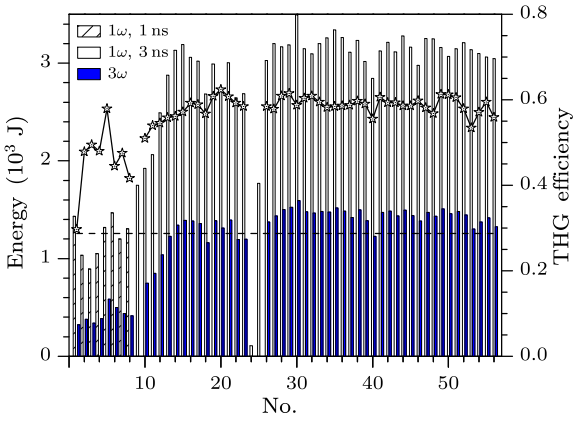


Fig. 2. Energy and THG efficiency of laser shots.

The experiment contained 53 laser shots and could be divided into three phases, as shown in Fig. 2. They were laser commissioning phase, laser conditioning phase and high-fluence operating phase. In the laser commissioning phase, 8 shots were fired for experiment preparation with low energy of 1200 J, pulse duration of 1 ns at the central wavelength of 1053 nm. The laser conditioning phase followed with 4 shots of ramped energy (increased from 1800 J to 3000 J at 1053 nm) and 3 ns duration for laser conditioning. It is believed that laser radiation of ramping energy could eliminate the possible super-low-damage-threshold defects and heal little initial damage sites.[6] Then 41

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shots of about 3000 J energy and 3 ns duration were fired during high-fluence operating phase. A typical near field beam image of 1053nm pulse is shown in Fig. 3. The upper-left corner of the beam near field was shielded from laser irradiation for future comparison tests off-line, and at the centre part there exists a baffle. The actual illuminated area is 616 cm^2 by measurement. For the 351 nm energy, it was measured at the target spot and should be divided by 92% due to the transmission loss from the component concerned to the target spot. The fluence on the first fused silica optics is about 1.9–2.8 J/cm^2.

To delay the sol-gel coating degeneration we separated the FOA from the target chamber. The components inside the FOA were operated in clean dry air at a pressure of 1000 Pa, separated from the environment outside by the window, and the hard vacuum of the target chamber by a shield (fused silica 3). We located two samples of the same sol-gel coating in target chamber (vacuum) and the FOA (1000 Pa clean air) respectively. Before the first shot, after the 22^{nd} shot and the last shot, we tested the transmission efficiency of the samples. The result is given in Table 1. It shows that the atmosphere of 1000 Pa clean dry air effectively delays the degeneration of the sol-gel coating thereby postpones the damage initiation and growth.

After each shot during the experiment, two CCD cameras and Questa (a long-working-distance microscope) installed on FOA were used to monitor the large-aperture components in-situ. One camera was behind the vacuum shield and the other one and the Questa in front of the window. Two halogen lights were put behind the vacuum shield for illumination. Thus we obtained the images of the components after each shot and observed the complete process of damage growth.

At the end of the experiment, the optical components in the FOA were disassembled and dark-field pictures of them were taken. The dark-field picture of the first fused silica is shown in Fig. 4. The component was severely damaged, while the others were nearly undamaged.

Table 1. Transmission efficiency of samples with sol-gel coating in FOA and target chamber.

Sample location	Sample	Test 1 (before 1^{st} shot)	Test 2 (after 22^{nd} shot)	Test 3(after the last shot)
FOA	k-28	100%	99.9%	92.1%
Target chamber	k-19	100%	95.3%	90.6%

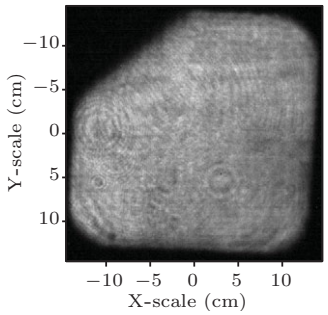


Fig. 3. Typical beam spatial near field profile of 1053 nm laser.

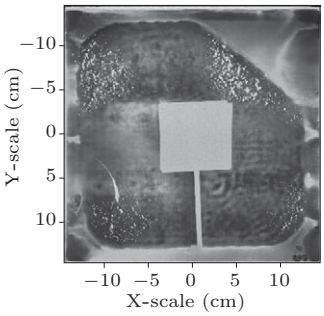


Fig. 4. Dark-field images of the first fused silica optics.

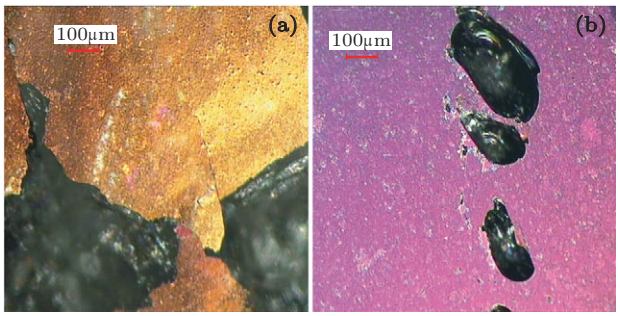


Fig. 5. Micrograph of (a) damage sites (b) scratch.

The severely damaged optics is the first fused silica component with grating on the output surface and AR (anti-reflection) coating on the input surface. Compared to the damage on witness samples (mm size fused silica plates) we observed that the damage threshold on this component is about 3 to 6 times lower. This could be explained by the aperture-size effect. Interestingly, there are about 5 cm×5 cm densely damaged areas of hundreds of damage sites initiated at the four corners and an arched scratch of 10 cm growing out on the input surface (Fig. 4). On small aperture systems the damage always initiates on the output surface and distributes randomly. We will provide an explanation later. The morphology of the damage sites and the scratch were examined by a microscope (Fig. 5).

The sites were typical damage crater with a melting pit surrounded by peeled and/or cracked substrate (Fig. 5(a)). The white crystal at the centre of the pit implied redeposition of melted fused silica. The peeling and/or the crack suggested the existence of shockwave and stress. The morphology of the damage sites was in strong agreement with the micro-explosion model: the initial damage sites with modified material and weakened structure would strongly absorb the subsequent laser by the melting core and therefore achieve high temperature and give birth to a plasma micro-explosion which yields high stress and shockwave.[7] By magnifying the scratch we found it composed of numbers of tiny or large damage sites (Fig. 5(b)).

We chose four separately discernible sites and monitored their growth. After each laser shot, the area of each damage site was measured on the pictures. A growth plot with the area plotted vs shot number is shown in Fig. 6. The growth is linear with shot num-

ber. The data is fit to a linear line given by

$$S_{\text{area}} = A + B \cdot N,$$

Where S_{area} is the area of the damage site, N is the shot number, A and B are the fitting parameters. A pixel corresponds to about $0.1\,\text{mm}^2$ by calibration. Table 2 shows the fitting parameters.

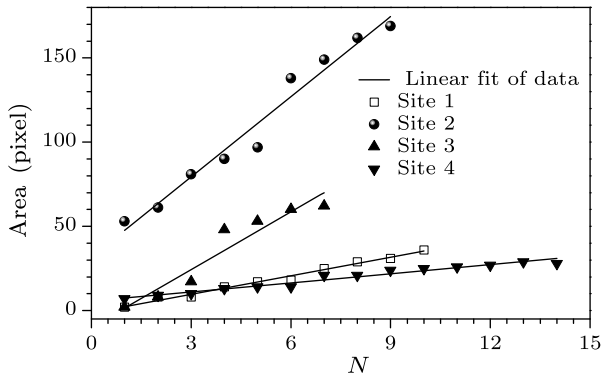


Fig. 6. Damage area growth vs. shot number of four sites.

Table 2. Linear fitting parameters of damage sites area growth vs. shot number.

	Initial area (pixel)	Final area (pixel)	A	B
Site 1	2	36	−1.4	3.67273
Site 2	53	169	31.86111	15.85
Site 3	2	62	−10	11.42857
Site 4	7	28	5.59341	1.80659

As listed in Table 2, the parameters are different. It is believed that the different mechanisms for damage initiation would cause different morphologies of damage sites and lead to different growth coefficients. However, there has been no way to relate the growth coefficient to damaging mechanism yet so far. Here we could try to explain it qualitatively with a developed model.[8] As we mentioned before, the crater consists a melting pit surrounded by peeled and/or cracked substrate. Observations of the damage growth show that the area grows mainly by the cracks. The model assumes that the melting core would absorb the laser energy and yield plasma in the crater whose pressure would open the cracks on the periphery of the damage spot. Thus the area of the damage site grows.

Assume that the plasma opens a crack of the length L by pressure

$$\sigma = K/\sqrt{L},$$

where K is the fracture toughness of the material which for fused silica is $0.75\,\text{MPam}^{1/2}$. The pressure caused by the plasma inside the crater is P. On the crack the pressure P_1 is

$$P_1 = P(R/L)^3,$$

where R is the initial radius of the crater.

When $P_1 = \sigma$, the crack opens and the surface peels off. At this time

$$L = R^{6/5}(P/K)^{2/5}.$$

Apparently the radial growth of the crater is L after one shot. Thus, the area grows with the shot number as

$$A_N = A_{N-1} + 0.7954\alpha^2 \cdot A_{N-1}^{1.2} + 1.7837\alpha \cdot A_{N-1}^{1.1},$$

where we define $\alpha = (P/K)^{2/5}$.

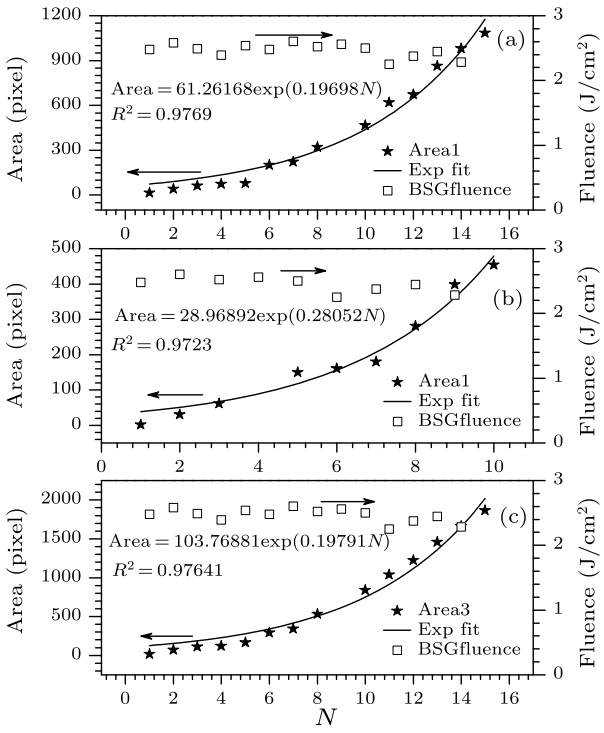


Fig. 7. Obscurations growth vs shot number of three areas.

The relation between A, the area and the shot number N varies with α which is decided by pressure P. As pressure P grows, the growth curve would change from linear to exponential gradually. Between damage sites with the same area but different cracking areas and melting area ratio, like site 1 and site 3, the pressure trigged by laser differs and hence changes the growth curve. The confirmation experiment of this speculation is underway.

Likewise we choose three areas for measuring obscurations which is an important index for optical lifetime. LLNL defined that when obscurations (sum of all the damage sites) reach 3% of the whole area, the component should be replaced. A growth plot with the obscurations plotted vs shot number is shown in Fig. 7. The growth is exponential with shot number. The data are fit to an exponential curve given by

$$S = a \cdot \exp(bN),$$

Here S is the area of the obscurations, N is the shot number, a and b the fitting parameters. Table 3 shows the fitting parameters. Also we measure the area growth of the scratch (Fig. 8) and the growth behaviour is in strong similarity with the obscurations.

Based on this and the microstructure of the scratch described earlier we conclude that we could treat scratch as a cluster of damage sites. The $1/b$ values are in the same magnitude (3.5–8.5 shots) indicating this is the number of shots to increase damaged area by e. This number, if accurately measured, could enable us to estimate the growth of the damage sites and predict the lifetime of the optics. However, the damage data we acquired here is relatively small. More damage experiments under operation conditions are needed to find an applicable $1/b$ value.

Table 3. Exponential fitting parameters of obscurations growth vs. shot number.

	a	b	Initial area (pixel)	Final area (pixel)
Area 1	61.26168	0.19698	15	1085
Area 2	28.96892	0.28052	2	389
Area 3	103.76881	0.19791	18	1865
Scratch area	33.02228	0.11857	27	315

The first fused silica optics is for beam sampling and tends to damage most severely of all components. It has something to do with the manufacture process.[9] It has been reported that a modified layer, called the Beilby layer, is formed during polishing.[10] This layer of approximately 10 to 100 nm covers subsurface cracks in the defect layer and contains nano-absorbers introduced from the grinding and polishing process, like Ce which we used as a polishing compound. The nano-absorbers especially Ce would strongly absorb the incident laser energy. For instance, 3 ns, 15 J/cm^2 laser pulse could heat a 10 nm diameter ceria sphere to 4000 K, therefore leading to a thermal explosion.[11] As a result, the existence of the Beilby layer lowers the damage threshold. Thus, during laser radiation the redeposition layer was first damaged. After the redeposition layer peeled off the subsurface layer was exposed and damaged. Damaged sites brought dust which would accelerate the damaging process. We conclude that the Beilby layer was responsible for the damage. The reasons are based on two aspects. First, fused silica optical components in FOA are wet etched with buffered HF solution before coating except the first one. Thus the second and the third fused silica optics were nearly undamaged while the first one was severely damaged in the experiment. Second, the difference of damage performance between the input surface and output surface of the first fused silica optics implies the effect of the Beilby layer. When polishing was carried out, to engrave the grating on the output surface with Ar ion beam, we rinsed the surface with 10% NaOH solution and then gelatinized it with light-sensitive glue. After that, it was sent to film anti-reflection coating on the input surface. For protection of the groove, the input surface was not etched by HF acid like other optics or cleaned like the output surface with NaOH. This could be the reason why the input surface is most severely damaged while the output surface is still under good condition. Nevertheless, we could not answer why the damage sites are mainly on the corners. In the planned further experiment, we would disassemble the optics and test it on the central part and the corner for damage threshold and damage growth data on small aperture systems.

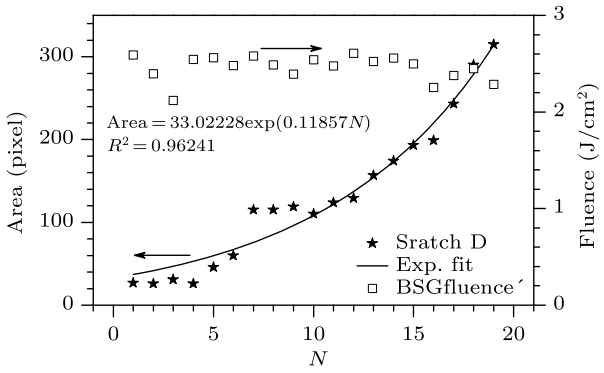


Fig. 8. Area growth vs shot number of the scratch.

In summary, we have monitored damage on large-aperture laser facility in-situ and obtained the damage growth data . The damage sites on the input surface grow linearly with the shot numbers. The growth coefficient differs largely. Obscurations and the scratch grow exponentially. It is concluded that the existence of redeposition layer is the reason for the damage, which necessitates the acid etching on the surface of all the components.

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