Laser-induced damage on large-aperture fused silica gratings

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(Received 13 January 2010; revised manuscript received 20 April 2010)

Two sets of laser-damage experiments on large-aperture fused silica optics have been carried out in a high-power laser facility. Severe damage has been found on the grating which presented dense craters on the front surface. This phenomenon is quite different from other fused silica optics, which are damaged on the rear surface. The damage possibility due to the redeposition layer was ruled out by acid-etching the grating's front surface. The remarkable stimulated Brillouin scattering (SBS) effect was observed in grating and the reason for the front surface damage is thought to be the backward SBS.

Keywords: laser-induced damage, grating, Beilby layer, stimulated Brillouin scattering

PACC: 6180B, 4270E, 4265C

1. Introduction

The lifetime in the UV of fused silica optics used in large high power laser facilities such as the National Ignition Facility in the United States,[1] the laser megajoule[2] in France, and the prototype of SG-III laser facility[3] in China has been the subject of extensive studies. It has been shown that at wavelengths of 351 nm the lifetime of fused silica optics is determined by both surface damage initiation and damage growth. Many researches were performed in the U.S.[4] and France[5] to understand the process of damage initiation and growth, and the strategies developed to improve the lifetime relying on reducing initiator density and using mitigation techniques to inhibit the growth of damage sites.[6] Similar studies were also conducted in China to advance the understanding on this issue.[7−9] However, most damage experiments were carried out off-line at small-aperture and low energy platforms. Due to the aperture-effect of the laser-induced damage, the difference could strongly affect the damage performance. Therefore we present and discuss the laser-induced damage phenomenon of large-aperture fused silica optics on the prototype of SG-III laser facility.

2. Experimental setup

The main specifications of the prototype of the SG-III laser facility are listed as follows: beam size 29 cm × 29 cm, wavelength 0.351 μm, output energy 1.6 kJ/0.351 μm/3.0 ns/beam, pulse duration 3.0 ns (square pulse). Two laser damage experiments were performed on this laser facility. In both experiments 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 which are a back grooved grating for beam sampling, a focusing lens and a vacuum shield. 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 is transformed from 1053 nm to 351 nm.

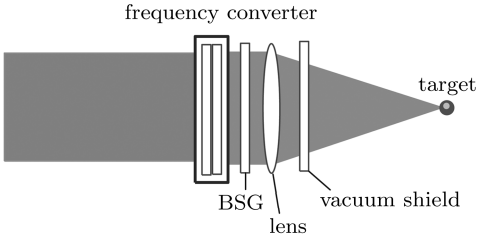


Fig. 1. Schematic of the optical layout configuration of the FOA.

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In the first experiment, 45 laser shots were fired which contained 4 shots of ramped energy (increased from 1800 J to 3000 J at 1053 nm) for laser conditioning and 41 shots of about 3000 J energy (at 1053 nm) for damage testing. It is believed that the laser radiation of ramping energy could eliminate the possible super-low-damage-threshold defects and heal the little initial damage sites and therefore postpone the damage initiation and growth. The energy of laser shots was shown in Fig. 2. It has to be pointed out that

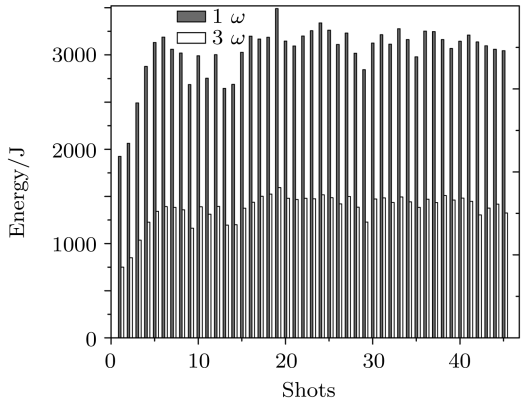


Fig. 2. Energy of laser shots in the first experiment.

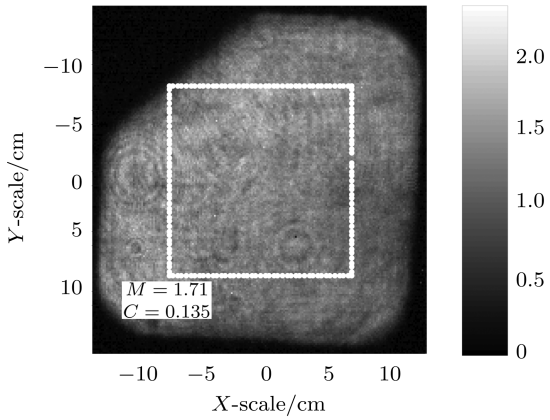


Fig. 3. Typical beam spatial near-field profile of 1053-nm laser. The modulation ratio (M) and the contrast ratio (C) are 1.71 and 0.135, respectively, in the calculated white square area.

the 351-nm energy 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 average fluence on the grating is about 1.9–2.8 J/cm^2. A typical near field beam image of fundamental pulse (i.e. wavelength at 1053 nm) is shown in Fig. 3. The near field modulation was kept below 1.75 during the experiments. The upper-left corner of the beam near the field was shielded from laser radiation for future comparison tests off-line, and in the centre part existed a baffle which was used to provide colour separation at the target.

3. Experimental results

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

The severely damaged optics are the first fused silica component with grating on the output surface and antireflection (AR) coating on the input surface. 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 grating surface, as shown in Fig. 4. More interestingly, almost all damage sites are located on the input surface while on small aperture systems the damage always initiates on the output surface. Compared to damage on witness samples (mm sized fused silica plates) the damage threshold on the grating is about 3 to 6 times lower.

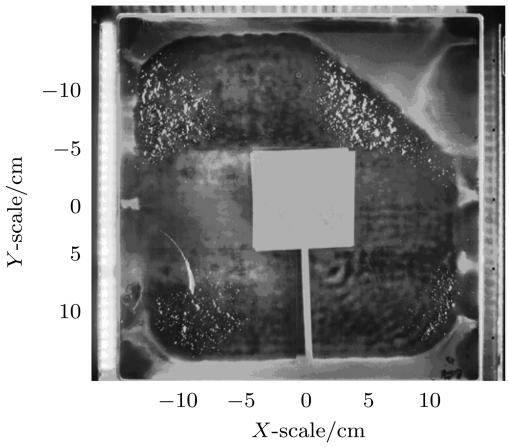


Fig. 4. Dark-field image of the grating in the first experiment.

The morphology of the damage sites and the scratch were examined by microscope. The sites were typically damage crater with a melting pit surrounded by peeled and/or cracked substrate. The observed white crystal in 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 good 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 temperatures and give birth to a plasma micro-explosion which yields high stress and shockwave.[10] By magnifying the scratch we found it composed of numbers of tiny or large damage sites.

The grating tends to damage most severely of all fused silica components and nearly all the damaged sites are located on the input surface. In order to figure out the reason for damage, we compare the manufacture process of the grating with other fused silica components. It appears that the damage of grating has something to do with the chemically modified layer, also called polishing or Beilby layer which is formed during polishing.[11] According to Ref. [4], this layer of approximately 10 to 100 nm covers subsurface cracks in defect layer and contains nano-absorbers introduced from 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, a 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.[12] As a result, the existence of the Beilby layer lowers the damage threshold. So during laser irradiation the redeposition layer is first damaged. After the redeposition layer is peeled off, the subsurface layer is exposed and damaged. Damaged sites bring dust which would accelerate the damaging process.

The Beilby layer is responsible for the damage on the grating's input surface, primarily for two reasons. First, fused silica optics in FOA is wet etched with buffered HF solution before coating except the grating. Thus the focusing lens and the vacuum shield are nearly undamaged while the grating is severely damaged in the experiment. Second, the difference of damage performance between the input surface and output surface of the grating implies the effect of the Beilby layer. When polishing is done, to engrave the grating on the output surface with Ar ion beam, we rinse the surface with 10% NaOH solution and then gelatinized it with light-sensitive glue. After that, it is sent to film anti-reflection coating on the input surface. For protection of the groove, the input surface is 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 in a good condition.

To verify our hypothesis, the second experiment with all new fused silica optical components is conducted and the front surface of the grating is also etched with buffered HF solution carefully before coating. In this experiment, for higher energy, the amplified laser in one beam path is injected to another beam path, and hence received further amplification. As a result, the laser pastes 18 Nd glass slabs in all, and an unprecedented high output energy is obtained.

In the second experiment 26 high fluence shots are contained, as shown in Fig. 5. The average fluence on the grating is about 3 J/cm^2 at 351 nm, 1 J/cm^2 higher than that in the first experiment. Unexpectedly, the grating shows severe front surface damage again after the experiment, as illustrated in Fig. 6. The densely distributed damage craters are mainly at the front surface. There are six long cracks on the surface, which are alternatively located at the front and the rear surface. It is intriguing that the six cracks are basically arrayed at the same 20 mm interval and the right-most crack is outside the boundary of the light.

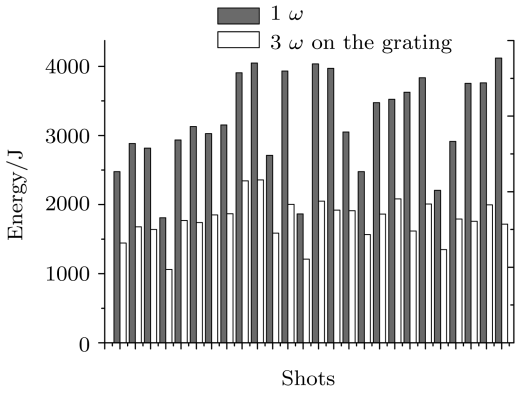


Fig. 5. Energy of laser shots in the second experiment.

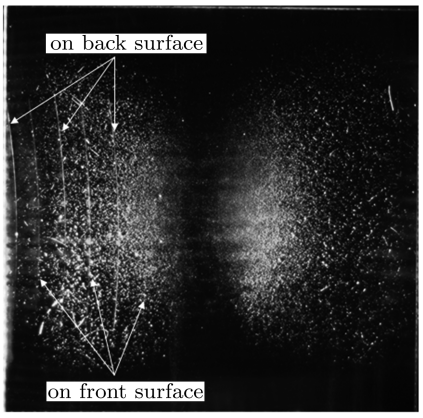


Fig. 6. Dark-field image of the grating after the second experiment.

Take a retrospective view at the development of the damage. In both experiments, the deterioration of the surface always started with the appearance of

ash-like material on the four corners. The foggy area gradually expanded inward. After a few shots, the cracks came out. Afterwards, the craters appeared on the front surface and its number was increasing with the shots.

The bizarre fact about the damage on the grating is that, unlike other optics, the damage craters are always on the front surface. In common belief, the nonlinearity would make the fluence on the rear surface bigger than the front surface, therefore the damage tends to happen on the rear surface. And many experiments on large-aperture optics have validated it.

We previously doubted that the thermo-absorbing inclusions at the front surface of a grating are responsible for the damage at the end of the first experiment. However, in the second experiment, we ruled out this possibility by acid-etching the front surface. The remaining possible explanation for the peculiarity is the stimulated Brillouin scattering (SBS).[13−16] The process of SBS can be described classically as a nonlinear interaction between the pump and the Stokes fields through acoustic waves. The SBS manifests through the generation of a frequency-shifted Stokes wave that propagates in any direction that could provide it with gain. In large-aperture optics, due to the large transverse dimension, the transverse SBS (TSBS) could have sufficient gain. If the transverse scatter light is strong enough, it would damage the lateral sides of the optics. This can be used to explain the ash-like material distributed on the four sides of the grating, as shown in Fig. 7.

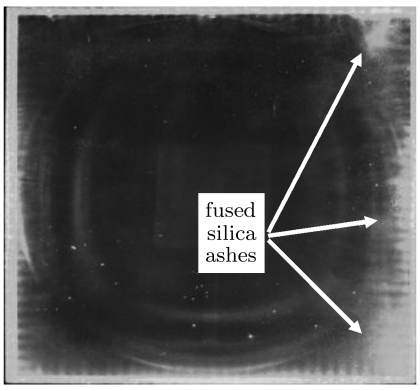


Fig. 7. Dark-field image of the grating during the second experiment.

For validating the existence of the TSBS, we pasted the thermo-sensitive paper on all four lateral sides of the grating in the second experiment. The paper detected the scattered laser on all four directions of the grating at the time the ash came out. Moreover, the scatter light had the strongest intensity in the direction perpendicular to the polarization of the incident laser. It is consistent with the theory that the SBS light would have the biggest amplification in the direction perpendicular to the polarization. We took the ash for analysing and found that the ash was fused silica powder. Therefore, we confirmed that the TSBS had happened and it had damaged the lateral sides of the optic which yielded the ash and contaminated the surface.

The experimental results confirm the existence of the TSBS. Besides the TSBS, we believe there was strong backward SBS[16] in the grating that was responsible for the dense damage craters on the front surface. When the laser propagates inside the grating, the backscatter light would propagate towards the front surface and show amplification. Finally, it will meet the rear part of the incident laser and cause high energy density on the front surface, hence damage the front surface.

More interestingly, in the second experiment we have found that the SBS effect in the lens, and the vacuum shield is much weaker than in the grating. Moreover, from the 16^{th} shot, we have moved the vacuum shield before the grating and found the transverse SBS too. But the intensity of the transverse scatter light is not as strong as in the grating. After the experiment, there is no damage on the front surface of the vacuum shield, which means the backward SBS is not distinct. In addition, there are no cracks of the special distribution pattern on the shield.

The unique damage phenomenon and remarkable SBS effect on the grating are related to the special structure of the grating, which has 20-nm deep grooves on the rear surface. The grooves would strongly scatter the light, hence provide the seed noise and initiate SBS. Whereas SBS in other fused silica optics such as lens and vacuum shield begins from the spontaneous initiation which is much lower than the seed noise scattered by the groove on the grating.

To validate the assumption that the front surface damage is primarily due to the SBS effect on the grating, we plan the third experiment in which the laser bandwidth will be enlarged to inhibit the SBS effect and it is in preparation.

4. Conclusion

In summary, we have presented and discussed the special laser-damage phenomena of a large aperture fused silica grating. The damaged sites are almost located on the front surface of the grating, which is different from other fused silica optical components in which the damage tends to happen on the rear surface. The damage possibility due to the redeposition layer was ruled out by acid-etching the grating's front surface. The remarkable SBS effect was observed in grating and the reason for front surface damage is thought to be the backward SBS. Further experiments are planned to confirm this assumption.

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