CHIN. PHYS. LETT. Vol. 26, No. 9 (2009) 097901

Explanation of Laser-Induced Damage Behavior of Fused Silica in a Large-Aperture Laser using a Small-Aperture Damage Test

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(Received 25 February 2009)

Laser-induced damage is a key lifetime limiter for optics in large laser facilities. Fused silica is tested to find the damage threshold on two different laser facilities of different apertures. The damage threshold shows that the corners of the component are less damage resistant. The acid etch on a corner does not effectively increase the damage threshold. A statistics-based model is presented to extrapolate the threshold data in a small-aperture test to predict the damage threshold under functional conditions.

PACS: 79. 20. Ds, 42. 70. Ce

Research on inertial confinement fusion (ICF) has recently progressed rapidly. In 2009, Lawrence Livermore National Laboratory (LLNL) in the US announced that the National Ignition Facility (NIF), the largest laser facility in the world, was 99% completed.[1] The SG-Ⅲ laser facility in China is also under construction.

Since they routinely bear high-energy laser shots, most large-aperture optics ($\sim$ m^2) within ICF lasers are prone to damage, especially fused silica optics in the final optic assembly (FOA).[2] In order to run the laser facility safely and reduce the replacement cost for the optics, it is imperative to have a thorough understanding of the in-situ damage behavior and set up a lifetime model of large-aperture optics. However, most damage experiments can only be conducted off-line at small-aperture ($\sim$ mm^2) and low-energy laser platforms instead of with ICF lasers. It is highly desirable to extrapolate the results of small-aperture damage tests to predict the damage performance of large-aperture optics under functional conditions. After completing the in-situ experiment on a high-power laser facility to obtain the damage behavior of large-aperture fused silica optics at 351 nm laser irradiation,[3] a damaged fused silica component was disassembled and received a damage test with a small-aperture laser beam. In this Letter, we present the results and a discussion.

The details of the large-aperture damage experiment were described in Ref. [3]. The large-aperture laser is capable of 1.6 kJ/351 nm/3 ns/beam output energy. We monitored the damage initiation and growth on large-aperture fused silica in the FOA. In the experiment, the upper-right corner and the central part of the component were shielded from laser irradiation (Fig. 1). The irradiation area was about 616 cm^2 by measurement. The damage mainly occurred at the four corners of the input surface, for reasons that were unclear. We did not find hot spots on the four corners and the modulation ratio of the beam field was kept under 1.75 in the experiment. We speculated that the corners might be less damage resistant. The damage began at about 1.9 J/cm^2 fluence and the damage craters continued to grow with repeated incident laser shots. We concluded that the thermal-absorbing defects in the redeposition layer were responsible for the damage.

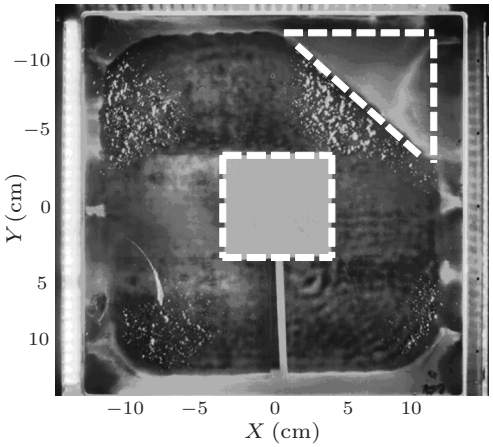


Fig. 1. Photograph of the tested fused silica. The four corners were damaged in a large-aperture test and the two areas bounded by white dashed lines were tested by a small-aperture laser.

To confirm our speculations, we disassembled the damaged fused silica after the experiment. We cleaned the damaged surface with water and ethanol to remove dust and possible contamination. Then we restored the non-irradiated parts to their original condition (white lined in Fig. 1). After cleaning, we etched the upper-right corner on the input surface with hydrogen fluoride (HF) acid of 1% concentration for 5 min to eliminate the redeposition layer. Afterwards, we conducted a damage test on the conditioned fused silica at a small-aperture laser platform (Fig. 2). The testing laser was a Nd:YAG laser of 355 nm wavelength and 6.4 ns pulse duration. The laser spot on the sur-

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face was about 1.55 mm^2 by measurement. The CCD and the illumination light are for damage imaging.

We tested sites in four areas at the two surfaces of the fused silica: the damaged-and-conditioned surface (A) and the undamaged surface (B) for comparison. The sites are indexed by their locations as follows: A-corner: the etched corner of surface A, A-center: the non-etched central part of surface A, B-corner: the corresponding corner of surface B, B-center: the corresponding central part of surface B.

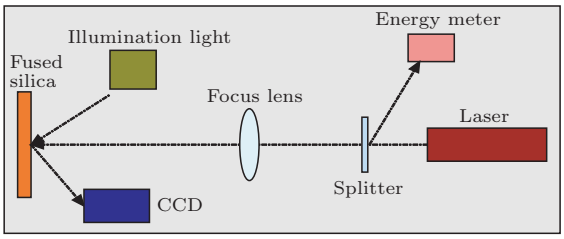


Fig. 2. Scheme of the small-aperture damage test platform.

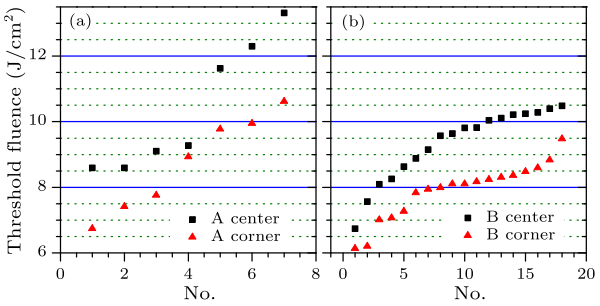


Fig. 3. Damage threshold fluence of tested sites on the two surfaces.

In the experiment, we increased the laser fluence until the damage occurred. Figure 3 shows the threshold fluence of the tested sites on the two surfaces (fluence scaled from the temporal pulse width of 6.4 ns to 3 ns by $\tau^{0.35}$). The damage threshold fluence scatters at every site. Table 1 shows the maximal, minimal and average threshold fluences. Generally, the threshold is higher at the center than at the corner of the two surfaces. This is consistent with the phenomenon that the corners are damaged first and most severely in the large-aperture experiment. With the small-aperture beam, the experiment excludes the influence of light modulation and confirms our explanation that the corners have lower threshold than the central. This might be caused the by manufacturing or polishing process, which needs further inspection. In Ref. [4], with controlled etch depth, the conditioned surface of the fused silica should have a minor improvement over non-etched surfaces. However, from Table 1 and Fig. 3, the HF acid etch has not effectively improved the damage threshold of the A-corner. We suggest that without a sophisticated method of controlling the etch depth, acid etch might not be an applicable way for us to withhold damage initiation.

Noticeably, even the lowest threshold in all the tested sites is much higher than the 1.9 J/cm^2 threshold fluence of the in-situ damage. It was also observed in experiments carried out by others that large-aperture optics will incur catastrophic damage by fluence lower than the damage threshold measured with small samples.[5] Here we present a statistics-based model to quantitatively explain this observation.

Table 1. Data on damage threshold fluence at the four test areas: maximal, minimal and average threshold fluences.

Tested area	Tested numbers	Minimum fluence (J/cm^2)	Maximum fluence (J/cm^2)	Average fluence (J/cm^2)
A-corner	7	6.74	10.62	8.74
A-center	7	8.60	13.32	10.40
B-corner	18	6.13	9.47	7.90
B-center	18	6.74	10.48	9.33

The surface damage is caused by the absorbing defects introduced in the grind and polish process.[6] Assuming the spatial distribution of the defects on the surface is a Possion distribution

$$X \sim P(\lambda),$$

the possibility of having k defects in area s can be expressed as[7,8]

$$P\{X(s) = k\} = (\lambda s)^k e^{-\lambda s}/k!.$$

The Possion distribution requires that the defects be distributed randomly and independently, which in this case is reasonable. Here λ is the distribution parameter. Then the probability of finding no defect in area s can be expressed as

$$U = P\{X(s) = 0\} = (\lambda s)^0 e^{-\lambda s}/0! = e^{-\lambda s} = e^{-N},$$

$$N = \lambda s.$$

This is the probability of the area s being safe under laser irradiation. Hence, the damage probability of the area s is[8]

$$P = 1 - U = 1 - e^{-N}.$$

Likewise, we assume that $C(I(s))$ is the density distribution of the damage threshold fluence of the defects, C is the density of the defects and $I(s)$ is the threshold fluence. Therefore, we can rewrite N as

$$N = C^* s = \int C(I(s))ds, \quad I > I_T,$$

$$P = 1 - \exp(-N) = 1 - \exp\left(-\int C(I(s))ds\right),$$

where I_T is the lowest threshold fluence. In the following discussion, we write $I(s)$ as I for convenience. For the polishing and grinding induced defects, we can use a two-parameter Weibull distribution to describe the defect size distribution.[9] The probability density function and the cumulative distribution function are

$$f(x) = \alpha\beta x^{\beta-1} \exp(-\alpha x^\beta),$$

$$C(x) = 1 - \exp(-\alpha x^\beta), \ \alpha > 0, \ \beta > 0, \ x > 0,$$

where x is the size of the defect and $C(x)$ is the normalized cumulative density of defects of size smaller than x. Therefore, $C(x)$ represents the percentage of the cumulative density of defects of size smaller than x and is always smaller than 1.

Because the fused silica is very weak in thermal absorbtion, we can neglect the thermal diffusion from the defects to the matrix. Then the temperature rise of the defect can be expressed as

$$\Delta T = 3Q/(4C_i\pi x^3),$$

$$Q = I\tau\varepsilon\pi x^2,$$

where Q is the heat absorbed by the defect, C_i is the heat capacity, ε is the dielectric constant of the defect, and τ is the pulse length of the laser. We define that when the temperature reaches a critical value, the damage occurs. Hence the threshold fluence can be expressed as

$$I = 4xC_i\Delta T_{\text{critical}}/(3\tau\varepsilon).$$

Thus the damage threshold I is proportional to the defect's size x. It can be rewritten as

$$I = qx, \quad q = 4C_i\Delta T_{\text{critical}}/(3\tau\varepsilon).$$

Substituting I for x in $C(x)$, $C(I)$ can be expressed as

$$C(I) = 1 - \exp(-\alpha(I/q)^\beta) = 1 - \exp(-\alpha q^{-\beta}(I)^\beta).$$

Here the form of $C(I)$ is similar to $C(x)$ and can also be written as

$$C(I) = 1 - \exp(-\alpha I^\beta).$$

We should pay attention the fact that this is the normalized form of $C(I)$. For the actual form of $C(I)$, we should multiply by a constant K, which gives

$$C(I) = K(1 - \exp(-\alpha I^\beta)).$$

Knowing the form of $C(I)$, we obtain the final form of P,

$$P(I) = 1 - \exp\left(-\int K(1 - \exp(-\alpha I^\beta))ds\right).$$

Here I stands for $I(s)$, which is the distribution of the fluence and is cumulative. It appears that the value of the irradiated area s will affect the damage possibility P. Because we usually define the damage threshold as the laser fluence corresponding to a certain damage probability, the measured damage thresholds for different tested areas s will be different, as we observed in our two experiments. Nevertheless, $C(I)$ is decided by the component itself and is not affected by the test area. Thus, we can use it as a tool to predict the damage threshold as follows.

First, based on our 14 test sites on the surface A, the damage possibility P of the small aperture test can be found. We converted the fluence distribution (Fig. 4(a)) to the damage probability curve (Fig. 4(b)) by defining $P(I)$ to be the ratio of the number of damaged sites under fluence I to the overall number of damaged sites.

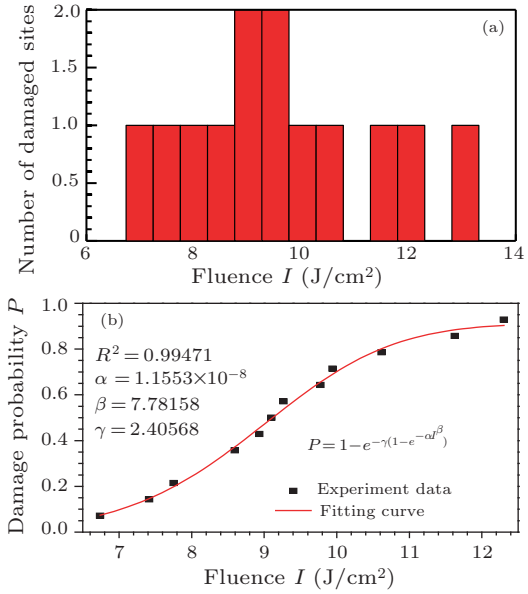


Fig. 4. (a) Damage threshold distribution of the 14 test sites on surface A; (b) the corresponding damage probability curve and its fitting curve.

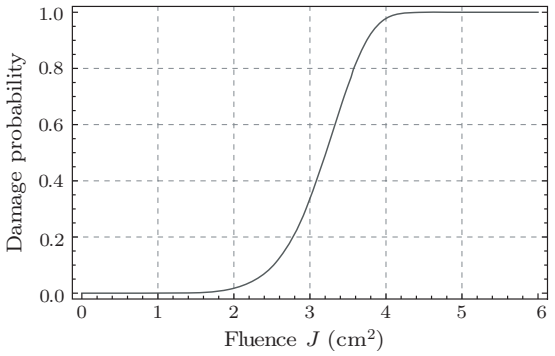


Fig. 5. Damage probability curve of the fused silica component in the large-aperture test.

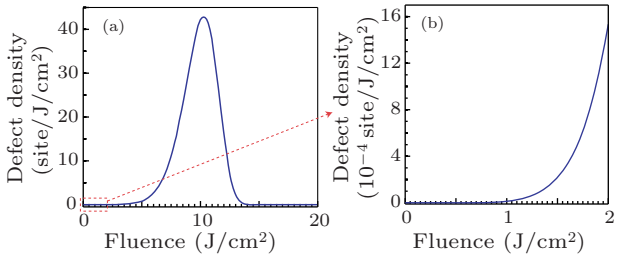


Fig. 6. (a) Probability density function $f(I)$ of the defects on surface A; (b) enlarged drawing of a segment of the $f(I)$.

Regarding the spatial form of the laser spot as approximately flat-topped, we can rewrite P as

$$P = 1 - \exp(-sK(1 - \exp(-\alpha I^\beta)))$$

$$= 1 - \exp(-\gamma(1 - \exp(-\alpha I^{\beta}))),$$
$$s = 1.55\,\mathrm{mm}^2, \quad \gamma = sK.$$

Fitting the expression to the probability curve, we draw Fig. 4(b). The unknown parameters can be determined: $\alpha = 1.1553 \times 10^{-8}$, $\beta = 7.78158$, $\gamma = 0.0155$, $K = 2.40568$. Given these parameters, the damage probability curve of the fused silica under the full-aperture test ($s = 616\,\mathrm{cm}^2$) can be easily calculated by substituting s in the exponent (Fig. 5). Also $f(I)$ of this fused silica is known (Fig. 6). From $f(I)$, the fluence corresponding to the density of one defect in the $616\,\mathrm{cm}^2$ surface ($1/616\,\mathrm{cm}^2 \approx 0.0016\,\mathrm{cm}^{-2}$) is about $2\,\mathrm{J/cm}^2$. This is close to our observation in the large aperture test that the damage started under $1.9\,\mathrm{J/cm}^2$. From the damage probability curve of the fused silica (Fig. 5), we can easily predict the possibility of damage at a given fluence. For example, at the expected functional $3.5\,\mathrm{J/cm}^2$ fluence of our laser facility, about 70% of the defects would be damaged. This would be intolerable under the current surface quality of our fused silica.

In summary, we have examined the damage behavior of fused silica with a small-aperture laser and compared it to results we obtained at a large-aperture laser facility. The acid etch cannot effectively increase the threshold fluence. The in-situ threshold fluence can be predicted by threshold data obtained in the small-aperture test with a statistics-based model. This model is instructional and useful in practice. It enables us to predict the damage performance of optics by testing the large-aperture optics off-line with a small laser.

References

[1] Official website of Lawrence Livemore National Laboratory (LLNL) Https://lasers.llnl.gov/newsroom/project_status/
[2] Conder A et al 2008 *Proc. SPIE* **6720** 672010
[3] Huang W Q et al 2009 *Chin. Phys. Lett.* **26** 017901
[4] Hrubesh L W et al 2001 *Proc. SPIE* **4347** 553
[5] Kozlowski M R et al 1998 *Proc. SPIE* **3244** 365
[6] Feit M D et al 1998 *Proc. SPIE* **3244** 350
[7] Liu X S, Cheng H J and He L M 2000 *Probability and Mathematics Statistics* (Beijing: Science Press) p 39 (in Chinese)
[8] Feit M D et al 1999 *Proc. SPIE* **3578** 226
[9] Weibull W 1951 *Appl. Mech. Trans. ASME* **18** 293