Experimental study on characteristics of nanosecond laser-induced damage on optical elements

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To study how laser pulse wavelength will affect the damage characteristics of optical elements with different degrees of contamination, we compare the extent of damage on optical glass between nanosecond pulsed laser of 1064 and 355 nm wavelength, respectively, and reach the following conclusions: the surface quality of clean optical elements determines its own anti-laser damage capability; the damage probability of optical sample caused by ultraviolet radiation-induced organic contamination is much higher than the infrared radiation-induced one; and contaminated metal particles can lower damage threshold of optical elements by 2–3 times.

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In the high-power laser-driven inertial confinement fusion and other large optical system, the load capacity of the optical element exerts limit on the output of the high-throughput laser. As a wide band gap optical material, fused silica is widely used in high-power laser optics system. However, due to defects in the production process of the optical element surface and sub-surface or surface contamination due to volatile organic and metal particles in a vacuum system, the damage threshold can be greatly reduced, thereby adversely affecting the output flux, energy conversion efficiency, and stability and reliability of operation on the whole system. American Livermore Laboratory and French Atomic Energy Commission have long carried out research in this area, focusing on both experimental and theoretical research on the reduced damage threshold caused by metal particles and organic volatiles contamination on fused quartz substrate, thus greatly enhancing the anti-damage ability of optical elements[1–7]. Over the years, Allenspacher *et al.*[1–4,7–12] conducted research studies on mechanisms of laser-induced damage on optical elements, the main method is to simulate the behavior of laser-induced damage on optical elements, analyze injury situation, and study damage mechanism, which helps to further improve the laser device operating environment, and improve the anti-damage ability of optical elements.

Therefore, the study of surface defects on optical element or contaminant-induced injury law has great significance on improving the anti-damage ability of optical elements, prolonging their service life, and ensuring long-term operation stability of the laser system. Here related experimental research studies are carried out under the circumstance of SG II device damage, the results obtained will be helpful for operation and maintenance of the SG device series and providing reference data for device development.

Figure 1 shows a schematic diagram of a vacuum damage testing system. In these experiments, it is worth noting that some optical samples are exposed in the atmosphere, whereas some others are placed in a vacuum environment. Measurement methods include one-on-one method (i.e., irradiation of one point on the element at a time) and s-on-one method (using the same laser pulse energy, irradiating the same point on the element for s times during the same time interval). Damage points are then observed through microscope. In a given optical parametric condition, the damage probability of the optical sample is m/n, where m is the number of damage points observed and n is the number of irradiation points. Associated optical parameters are as follows:

1) Laser wavelength (irradiated samples) $\lambda = 1064$ or 355 nm.
2) The average laser energy $E = 30-120$ mJ.
3) Laser pulse width $\tau = 12$ ns.
4) Effective spot area of about $S = 0.134$ mm^2.

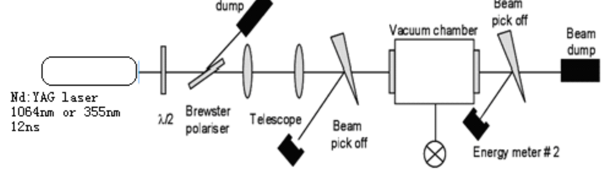

Fig. 1. Schematic diagram of vacuum damage testing system.

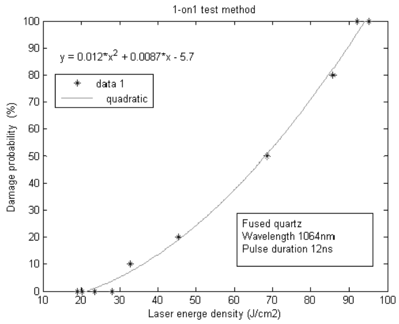

Fig. 2. Fitting curve of damage threshold and probability of fused silica by 1064 nm laser pulse in vacuum.

5) Substrate of the optical sample consists of fused silica glass and k9 glass, geometric dimension Φ 30×6 mm.
6) Vacuum degree 10^{-3} Pa.

We used lasers of 1064 and 355 nm wavelengths on fused silica glass samples to determine its “zero chance of damage thresholds.” Measurement method is the one-on-one method, corresponding to each of the laser energy, 10 points of the same optical sample were irradiated, a total of 10 kinds of energy result in a total of 100 measurement points. Then we observed these damage points under microscope. The results are shown in Figs. 2 and 3.

Figure 2 shows the result of a 1064 nm wavelength laser. The solution to the fitting curve equation leads to the “zero chance of damage threshold” of fused silica with energy density $E_{\mathrm{th}} = 22$ J/cm^2.

Figure 3 shows the result of a 355 nm wavelength laser. Solution to the equation leads to 18 J/cm^2 for the “zero chance of damage threshold” of fused silica. Analyzing from the thermal injury mechanism, the reason for a lower damage threshold of fused silica with 355 nm wavelength laser irradiation than with 1064 nm wavelength laser irradiation is that fused silica’s absorption rate of 355 nm laser is nearly 6–7 times greater than that of 1064 nm laser[13].

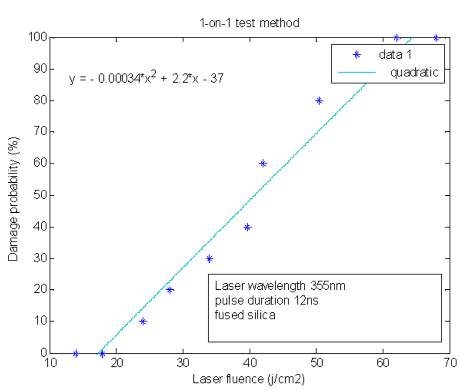

Fig. 3. Fitting curve of damage threshold and probability of fused silica by 355 nm laser pulse in vacuum.

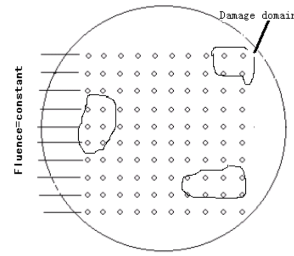

Fig. 4. Regional distribution of laser damage spots.

Additionally, when doing damage experiments on non-contamination samples, we found whether the material is glass or quartz, when the laser flux approaches damage threshold, and the number of laser irradiation points $N > 200$, then the damage points of the sample presents a regional distribution. This shows that damage of non-contamination sample is mainly caused by initial defects on sample surface, as only initial defects on sample surface and sub-surface can lead to regional distribution, as shown in Fig. 4.

To further confirm this judgment, we compared the anti-damage ability of optical samples with different processing quality. We found that the higher the sample surface smoothness, the stronger the ability, as shown in Table 1. Although optical samples differ in processing technology and quality standards, defects or initial damage degrees on sample surface and sub-surface are not the same. These initial damage points (or initial defects) will have a strong absorption of incident light to form a heating center, resulting in partial damage of the sample. Thus, improving processing technology and quality are basic measures to enhance optical elements’ load capacity.

It is also found that even with the same optical samples of the same processing quality, whether they had ultrasonic cleaning prior to the test or not can lead to different damage thresholds. This is because in the processing of optical samples, the optical surface will produce sub-micrometer defect points, which can absorb optical sticky grinding materials using the van der Waals force, such as carborundum particles or other impurities. Under laser irradiation, these impurities will absorb the incident light, heating its surrounding to a high temperature and causing the original quartz forbidden band to collapse, thus resulting in the local thermal explosion on quartz surface. Usual cleansing methods cannot remove these adsorbed impurities, only special cleansing methods such as the ultrasonic can partially remove the impurities adsorbed on optical surface.

Sample (JGS1) 1: Surface quality 80/50, surface accuracy $< 1.5\ \lambda$.

Sample (JGS1) 2: Surface quality 40/20, surface accuracy $< 0.25\ \lambda$.

In the experiment, we randomly scattered 300 mesh (48 μm diameter) stainless steel particles on the incidence plane of fused silica glass sample, as shown in Fig. 5(a). The results were as follows:

Table 1. Damage Threshold of Samples with Different Surface Quality (Sample 2 s-on-one, t = 12 ns, λ = 1064 nm)

Sample	**Sample 1**	**Sample 2**	**Not Ultrasonic Cleaning (Sample 2)**	**Ultrasonic Cleaning (Sample 2)**
Damage Threshold (J/cm^2)	22	42	42	55

1) We irradiated non-contamination optical sample with laser of about 5.6 J/cm^2 energy density and 1064 nm wavelength, using one-on-one testing method, irradiating 50 points, each point for once. We then observed damage points under microscope and found no sign of damage.
2) We used laser of the same energy density to irradiate quartz optical sample with metal powder contamination from the front surface (i.e., the metal powder is on the front surface of fused silica), with a total of 50 irradiation points, each point for once. We then observed damage points under microscope and found significant damage points on input surface, as shown in Fig. 5(b). The exit surface is not damaged, as shown in Fig. 5(c).
3) Under the same conditions, we changed incident light to the back surface (i.e., the metal powder is on the back surface of fused silica). We then found no damage point on the quartz input surface while damage on the exit surface, as shown in Fig. 5(d).

Except different laser wavelengths, we used same conditions as above. We used one-on-one method to test the damage probability of quartz sample with metal contamination. Compared with above experiment, the damage threshold induced by two kinds of wavelength is similar, as shown in Fig. 6.

The laser energy absorbed by metal fragments on fused silica sample surface is the product of the laser pulse flux F and the absorption coefficient A. Because the laser pulse is very short and metal fragments are very thin, the temperature inside the fragments is even. This heat source can be approximated as a source point, the energy used for evaporating metal fragments is less than the energy converted into the quartz sample, and the local temperature of the sample surface can therefore be expressed as[14]:

$$T = \frac{AF}{\rho c\sqrt{\chi\tau}} = \frac{AF}{\sqrt{\tau}}10^5 K, \qquad (1)$$

where the flux can be expressed as J/cm^2 and pulse width as ns. Eq. (1). can be used to estimate the local temperature of sample surface, when A = 0.01, τ = 12 ns, F = 10 J/cm^2, the sample surface temperature can reach up to 2900 K, enough to cause quartz surface damage.

We randomly applied fresh (unheated) 703 silicone and vacuum lubricating oil on one side of the K9 glass sample to form a coating layer, then used 1064 nm wavelength laser with different pulse energy to irradi-

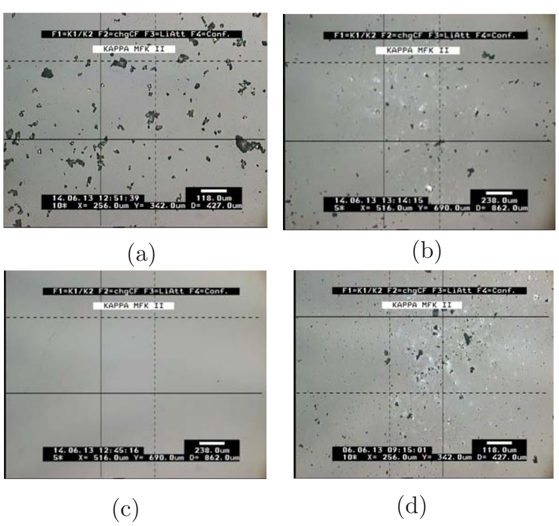

Fig. 5. (a) Metal powder on sample surface, (b) laser radiated front sample surface, (c) laser radiated back sample surface (no damage on exit surface), and (d) laser radiated back sample surface (damage on exit surface).

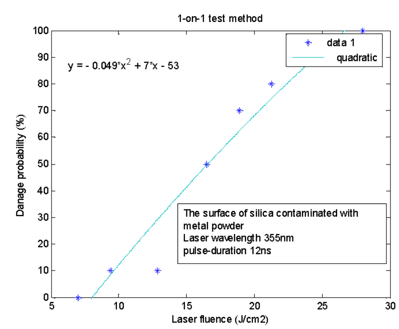

Fig. 6. Damage probability of metal particle contaminated fused silica sample

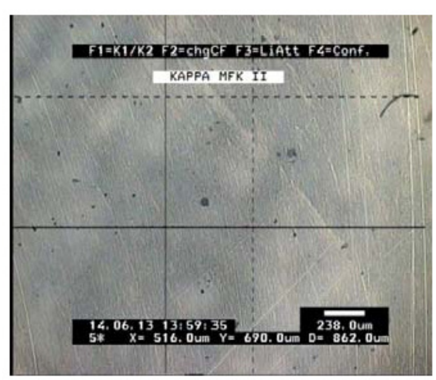

Fig. 7. 703 silica contaminated optical surface after laser radiation.

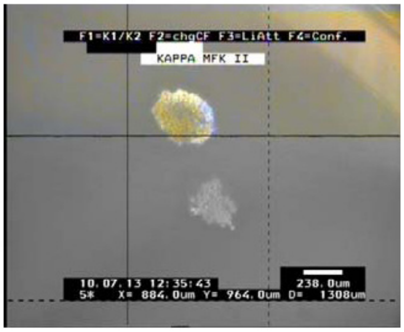

Fig. 8. Laser damage caused by heated 703 silicone.

ate the optical surface, using s-on-one mode to irradiate each point for 50 times. The pulse energy density $E = 15$ J/cm^2. We found no significant damage points, see Fig. 7.

Using Fomblin grease as contamination source can generate similar results. This finding is consistent with domestic and foreign reports[15–18], that the damage mechanism of organic contamination is different from that of metal particle contamination, as light absorption of organic pollutants is too small, temperature cannot be immediately raised to the damage threshold. Even when using the s-on-one irradiation, if the irradiation time is less than a 1000, damage phenomenon is difficult to observe before the silica gel is decomposed into other active chemical groups. Usually, only when silicone compound is heated into silicon dioxide or other hypoxia groups will damage phenomenon occur[19].

According to related literature, only under heated condition will silicone change into additional silicon dioxide. We heated a 703 silicone-coated side of K9 glass to a temperature of 350 K in advance. Then using the s-on-one laser irradiation, we observed the damage situation. Experimental conditions are laser energy density $E = 14$ J/cm^2 and $s = 50$, *ceteris paribus*. We found damage points on the surface of optical materials (two actual irradiation points), see Fig. 8.

Different theories concerning the organic contamination damage mechanism are each confined to given experimental conditions. One theory states[18] that one of the reasons that quick optical laser damage occurs in vacuum system is the photochemical mechanism. This photochemical damage mechanism may include two aspects, one is the chemical reaction of pollutants caused by multi-photon or two-photon under laser action, etching the optical surface to cause damage. The other possible mechanism is that the chemical reaction process has produced a number of active intermediate groups and ions, which continue to participate in the chemical reaction to cause damage.

We believe that this result may be due to after effects of heat reaction, some silica gel's molecular structure will decompose to produce many active intermediate groups and ions, which then form a heating center, resulting in laser damage.

We used 355 nm wavelength laser and one-on-one method to test the damage probability of quartz samples with organic contamination. The results are as follows:

1) Damage probability of fused silica glass sample with Fomblin vacuum grease contamination Table 2).

Sample A: Surface coated with a layer of Fomblin vacuum grease.

Sample B: Sample A after degreasing solvent cleansing, the surface still has minimum traces of grease.

Sample C: Surface coated with a layer of Fomblin vacuum grease, see Fig. 9.

Damaged sample is shown Fig. 10

We have conducted a number of verifications on the result, which is the UV radiation-induced damage probability of fused silica glass sample with grease contamination is much higher than the infrared radiation induced, and is immediate. The mechanism behind why UV damage on samples with organic contamination is so obvious remains to be further discussed. One acceptable explanation is that damage is the result of defects on optical surface and the coupling effect of organic pollutants. That is, when optical sample surface is absorbed with organic contamination, defects and the absorbed contamination could inter-couple; distortion at the sub-surface can produce high field intensity, so that the organics can produce non-linear absorption to result in a number of high-absorbency groups, causing damage to the quartz surface.

Table 2. Damage Probabilities of Different Samples (Laser Wavelength of 355 nm)

Laser Fluency (J/cm^2)	**Sample A Damage Probability (%)**	**Sample B Damage Probability (%)**	**Sample C Damage Probability (%)**
11.84	60	0	10
14	70	0	70
16.52	100	0	80
18.9	100	40	100
21.28	100	100	100
23.8	100	100	100

Fig. 9. Fomblin vacuum grease-coated optical sample surface.

Fig. 10. UV radiation-induced damage of fused silica samples with vacuum grease contamination (one-on-one testing method).

2) Damage probability of fused silica glass sample with 703 silicone adhesive contamination.

Table 3 lists the damage probability of fused silica glass sample with 703 silicone adhesive contamination.

Figure 11 shows the quartz damage by a laser flux of 16.5–18.9 J/cm^2.

In conclusion, we discuss laser damage of optical elements, comparing the damage degree on optical glass by 1064 nm wavelength laser and 355 nm nanosecond pulse laser, and reach the following three conclusions:

1) Different optical surface quality contributes to significant difference in shallow surface damage thresholds; ultra-smooth optical surface can effectively improve its anti-damage ability. Improving processing technology and quality of optical elements is the fundamental measure to enhance the load capacity of element.

Table 3. Damage Probability of Fused Silica Glass Sample Contaminated by 703 Silicone Adhesives

Laser Fluency (J/cm^2)	**Sample A Damage Probability (%)**
11.84	0
14	30
16.52	70
18.9	90
21.8	100
23.8	100

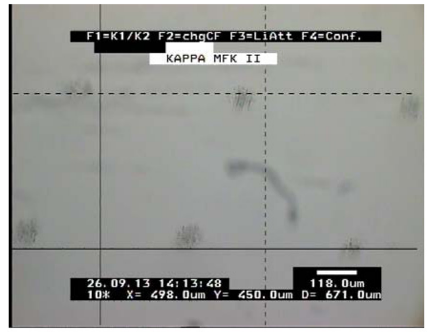

Fig. 11. UV radiation-induced damage of fused silica samples with 703 silicone contamination (one-on-one testing method).

2) UV radiation-induced damage probability of fused silica glass sample with organic contamination is greater than the infrared radiation induced; especially the distortion at the sub-surface can produce high field intensity, so that the organics can produce non-linear absorption, resulting in damage to the quartz surface. Therefore, the cleanliness of high-power laser devices (especially optical terminal equipment) should be strictly controlled.
3) Metal particle contamination can reduce the damage threshold of optical elements by 2–3 times, as it can reduce the load capacity of optical elements. We should consider stray light irradiation to nearby metal parts in the layout of laser path, minimizing the scattering of metal particles generated by the interaction of laser and metal. We recommend that before actual shooting practice, we should first launch several low-energy lasers to effectively remove the portion of metal residues on optical element surface.

Through damage experiments under different conditions and analysis of damage situation, we believe that the planar defects and volume defects caused production process of optical elements are the main reasons for reduced anti-damage ability of optical elements; during the operation optical devices, environmental and human-induced surface contamination will exacerbate the damage process. Therefore, improving the processing technology of optical elements and enhancing processing quality, increasing the cleanliness of the experimental environment, and reducing volatility of other materials in the device are the necessary premise for increasing the output flux of laser device and ensuring long-term stability of device operation.

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