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Growth of Laser Initiated Damage in Fused Silica at 527 nm

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ABSTRACT

The effective lifetime of optics is limited by both laser-induced damage and the subsequent growth of laser initiated damage sites. We have measured the growth rate of laser-induced damage in fused silica in both air and vacuum at 527 nm. For damage on the exit surface, the data shows exponential growth in the lateral size of the damage site with shot number. The exponential growth coefficient depends linearly on the laser fluence. The behavior at the fluence threshold for growth is contrasted to that observed at 351 nm. The growth rate was not significantly affected by either the wavelength of the initiating fluence or the presence of 10 torr of air as compared to vacuum. When the damage is located on the input surface, it has both a higher threshold for growth and does not grow exponentially.

Keywords: Laser damage, laser damage growth, laser damage growth threshold, UV fused silica.

1. INTRODUCTION

The lifetime of optics used in laser applications is limited both by laser-initiated damage and by the subsequent growth of the laser-initiated damage. Since a laser initiated damage site is typically only tens of microns in diameter, if it was stable on subsequent shots, the performance of the optic might be considered acceptable in many applications. If the laser initiated site is not stable and increases in size, the performance of the optic will degrade with the number of laser shots until it finally cannot be considered useful. Thus, it is the growth of laser-initiated damage, which generally dictates the lifetime, and consequently the true cost of optics for a laser application.

Typical damage experiments are centered on measurements of the damage threshold of fused silica; this work focuses on the growth of damage after laser initiation. The growth rate of laser-induced damage in UV grade fused silica has been measured at 527 nm under a variety of conditions. The data is contrasted to that measured for the same material at 351 nm. Measurements of growth rate have been made in vacuum and in air, on sites initiated on bare surfaces. The influence of the initial starting size on growth rate has been considered. The significant finding in this work is that the growth rate of the lateral size with shot number shows exponential behavior when the damage is located on the exit surface of the optic.

2. EXPERIMENTAL DETAILS

Laser damage initiation thresholds are typically measured with small beam laser systems where the beam profile is Gaussian and of diameter on the order of 1-mm. To make measurements of laser damage growth that are relevant to large beam areas as are found on the NIF and other high energy laser systems, it is necessary to use a beam with an area large relative to the initial damage size. At LLNL, a unique laser facility can provide a large area, 527 nm beam. The laser is the SLAB laser system[1]: a Nd: glass zig-zag slab amplifier, with SBS phase conjugation producing a near diffraction limited 1.053 μm output. This is the workhorse of the growth measurements. As used for these experiments it provides a 10 J, 527 nm, 17 mm x 17 mm square beam, with a 10 to 12 nsec FWHM near Gaussian pulse, at a rep rate of 0.5-Hz. This rep rate is limited by data collection rate, as the laser system can be operated at 5 Hz.

The layout for the experiments with the SLAB laser is shown in figure 1. The 1-micron beam is image relayed onto the experiment table where it is reduced from 2.5 cm x 2.5 cm to 1.7 cm by 1.7 cm and relayed to the frequency converter: a KD*P type I doubler. Both colors are then passed through a vacuum relay with a magnification of two before reflecting from two dichroic mirrors where the unconverted red light is dumped and the green is sent back through this same relay. The output of this relay is then passed through a second vacuum relay where it is spatially filtered before it is transported to the sample chamber. The sample is located in an image relay plane of the laser and the beam size on the part is nominally 5 mm x 5 mm.

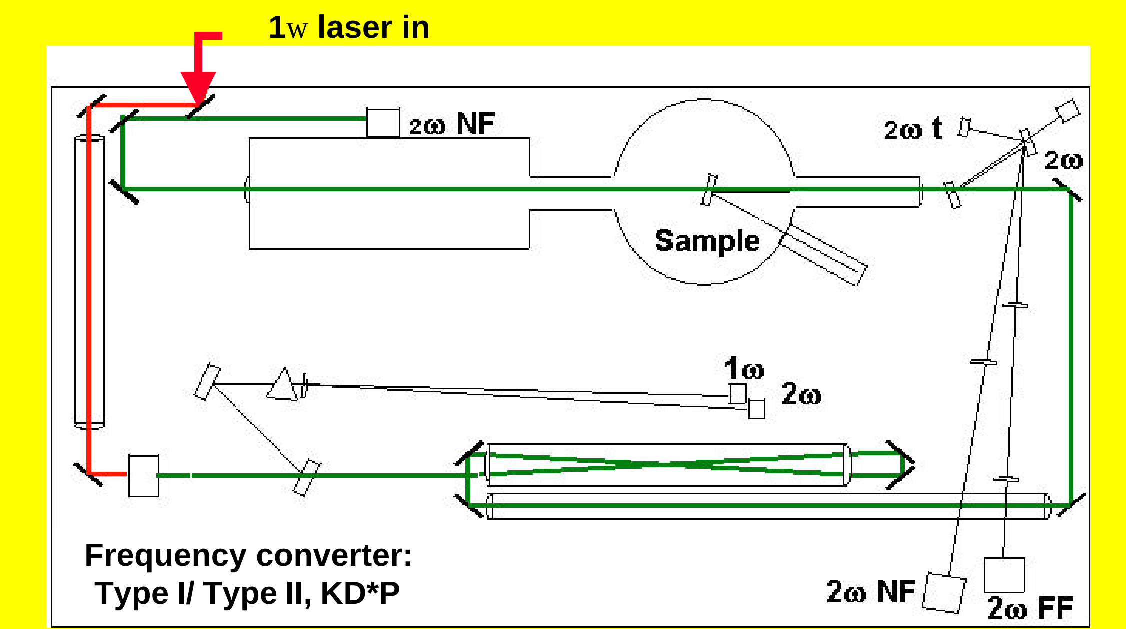
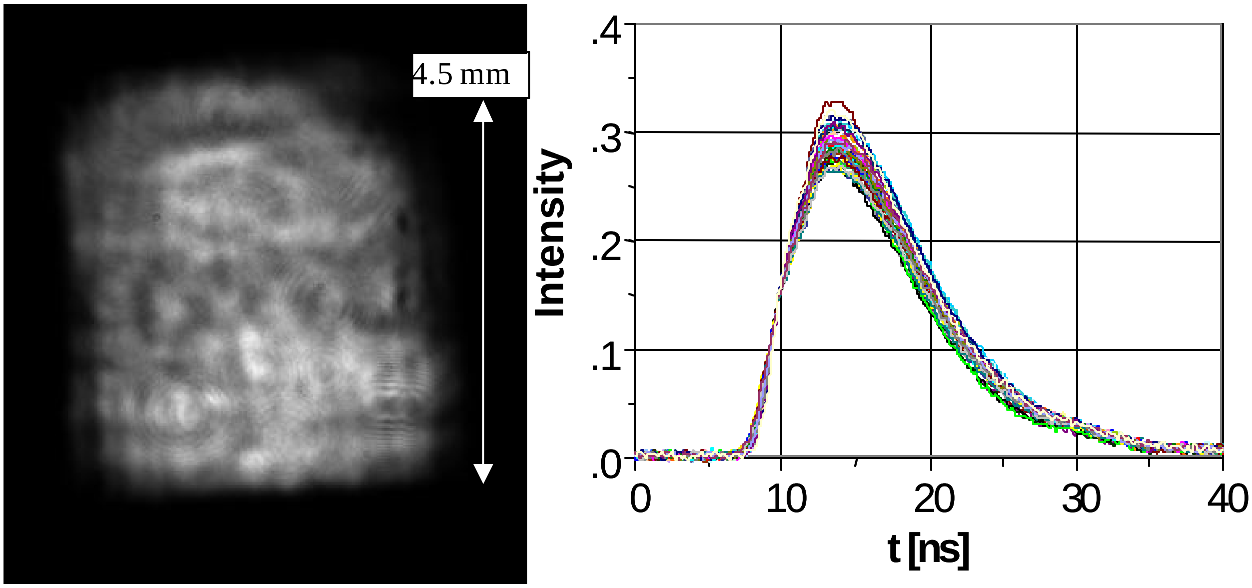


Figure 1. Layout of experiments.

The sample is housed in a stainless steel vacuum chamber, which is located in a class 100 clean room where samples up to 150 mm x 150 mm in size are handled during loading. For test series conducted in air at 10 torr, dry filtered high purity air is used to fill the chamber after it has first been pumped out to vacuum.

Laser beam diagnostics for the test beam on the part include measurement of the temporal pulse shape, energy and input & output beam near field intensity profiles. Diagnostics to measure the growth include a white light illuminated, long working distance microscope and CCD camera and scientific grade CCD camera viewing the transmitted light through the site. The workhorse for the growth measurements is a 16-bit scientific-grade CCD camera that samples the input beam. It is calibrated both for energy and for magnification and is used to set the fluence on the sample. A typical near field image of the beam on the sample is shown in figure 2a. The calculated statistics for this beam is a contrast of 25% over the central 60% of the area. In practice, the camera viewing the beam transmitted through the sample is used to locate the starting damage and the input camera is used to set the local fluence in a 1-mm patch surrounding the site. The lateral growth of the damage site can be measured either from the transmitted camera or from the microscope. The temporal pulse width is approximately 10.5 ns; an overlay of 50 temporal waveforms are shown in figure 2b, where the average FWHM=10.7 ns ± 3.4%.



(a) (b)

Figure 2. Typical 2w beam image and temporal profiles.

The samples were fused silica, UV grade Corning 7980, 2-inch round 1-cm thick and were super polished by SESO. Laser damage was initiated off-line at 351 nm with a single shot at a fluence level near 45 J/cm^2 with a 7.5 nsec FWHM Gaussian pulse. This high initiating fluence was chosen to produce repeatable damage spots in both size and morphology; even so there were variations in the site morphology. The lateral size and the number of individual pits in a site were cataloged. Typical sites and a table summarizing the morphology tracking is shown in figure 3 and Table 1 respectively. An example of the variation in the morphology obtained at this high fluence is clearly visible in figure 3. Table 1 indicates the typical fluences producing the various morphologies based on the number of individual pits and the lateral size encompassing all the pits. As an example, a site designated an L4 would have a lateral size of 200-300 µm and have more than 15 individual pits and would have required an initiation fluence of 45 J/cm^2. One sample was initiated at 527 nm where we found fluences greater than 100 J/cm^2 were required to produce sites of similar morphologies. The required fluences were at the upper limit of the fluence available so very few sites were produced. All samples were oriented with the initiated damage site on the exit face for the growth measurements except for three sites shot on the input surface.

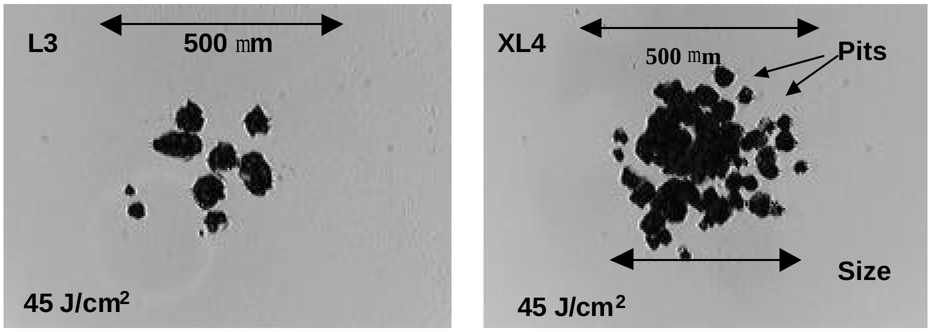


Figure 3. Micrographs of typical initiation morphologies.

	Number of pits	>15	6-15	2 -5	1
	Pit designator	**4**	**3**	**2**	**1**
Lateral size	**Size designator**	**Fluences that produce the morphology [J/cm^2]**			
>300 µm	**XL**	45	45		
200 – 300	**L**	45	45	45	
100 – 200	**M**		45, <35	<35	
30 – 100	**S**		<35	<35	
<30	**XS**				<35

Table 1. Classification of the site morphology and the required initiating fluence.

3. RESULTS

After each laser shot the lateral area of the damaged site was measured. The lateral diameter of the damage was calculated from the measured area by assuming a circular equivalent area. Two growth plots, obtained at different fluences, with the effective diameter plotted vs. shot number are shown in figure 3. What was found on these sites, as well as on all other sites showing growth, regardless of the starting morphology, is exponential growth of the lateral diameter with shot number. The data was then fit to an exponential curve given by

$$D = D_0 e^{aN} \tag{1}$$

where D is the effective diameter of the damage laterally, N is the shot number and α is the growth coefficient. The lateral growth spurts seen in these plots are typified by a few shots where crack growth seen on the perimeter is followed by apparent spallation of material with this cycle would repeating itself.

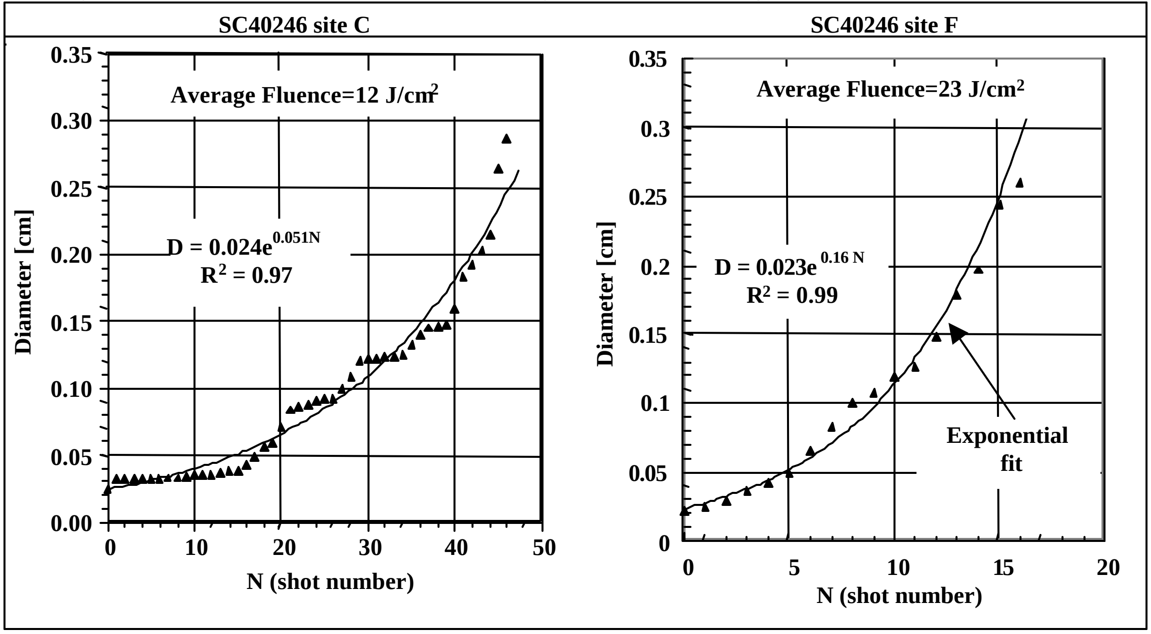


Figure 3. Typical lateral growth behavior showing exponential growth with shot number.

The catastrophic growth behavior plotted in figure 3 does not measure what typically is seen before a site exceeds its initial outside diameter. The large sites typically begin their growth on one or two internal pits. This type of behavior is shown in figure 4 where images from the online microscope of the first few shots of a growth sequence can be seen. For this site, it takes approximately 5 shots before the diameter of the site increases, even though changes are occurring starting on the first shot. The diameters plotted in figure 3 are obtained from the transmitted camera images. Typical data from this camera can be seen in figure 5. The measured growth coefficients are usually obtained from this camera. Occasional crosschecks with the microscope have verified that both cameras yield the same growth coefficient.

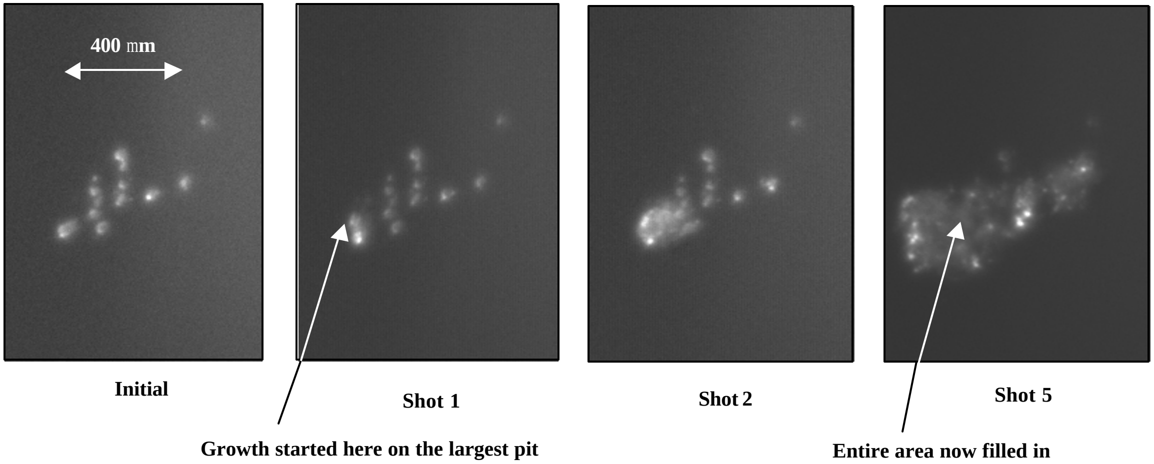


Figure 4. Microscope images of growing damage site.

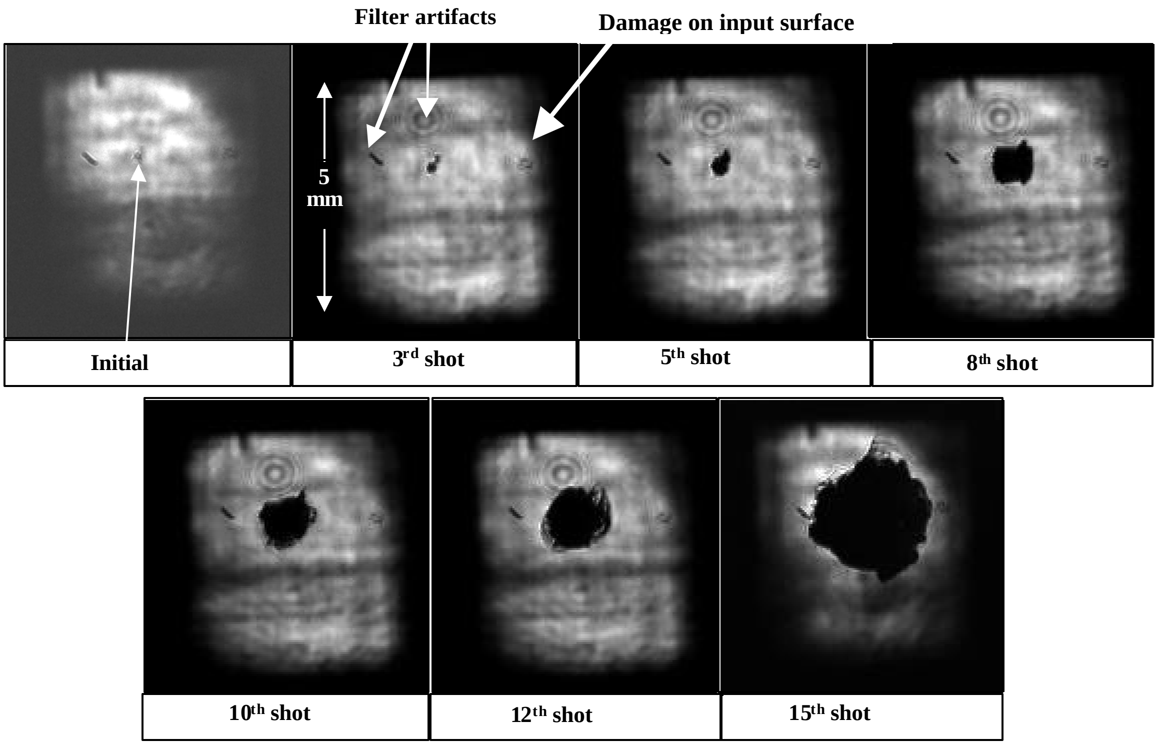


Figure 5. Transmitted camera images of growing damage site.

Plots of the growth coefficient vs. fluence at both 3ω and 2ω for many sites of initial sizes in the L3 to XL4 range show a threshold behavior for growth as can be seen in figure 6, which compares 3ω growth data[2] to the 2ω results. The linear fits to this data are the dark solid lines. No growth was measured at 2ω for fluences less than 12 J/cm^2. The growth coefficient at 3ω increases with fluence about 4 times faster than that at 2ω. No difference of the growth rate was observed between sites grown in vacuum or 10 torr of dry air. In addition, no difference of the growth was found between the sites that had been initiated at 2ω compared to those that had been initiated at 3ω.

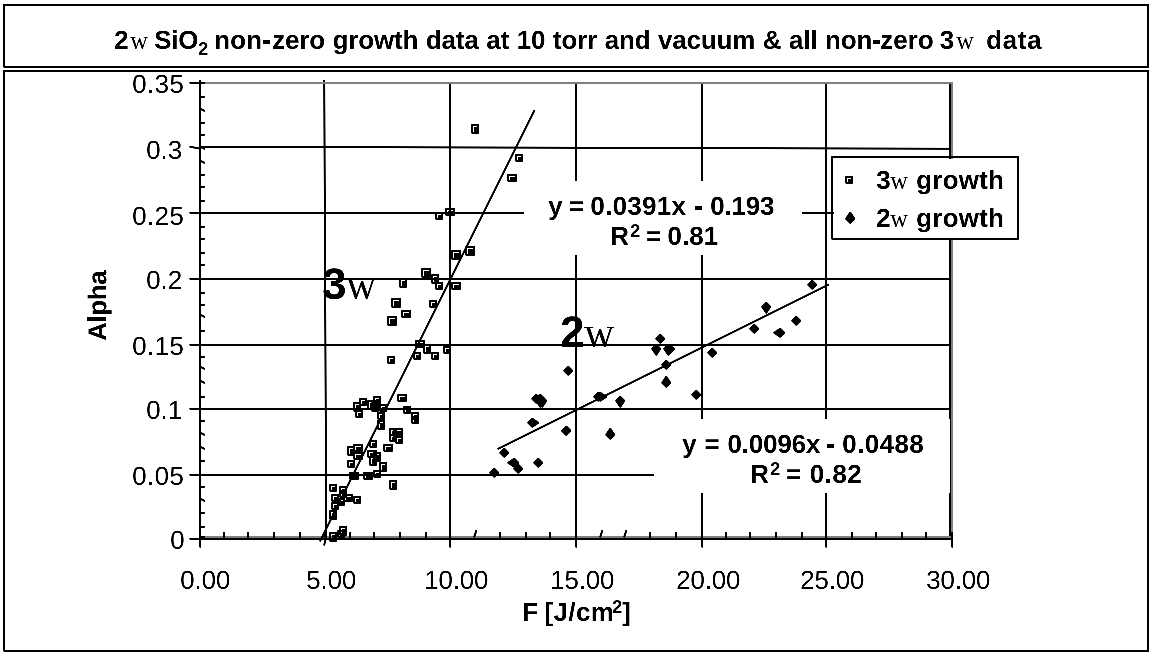


Figure 6. Plot of growth coefficients for 3ω and 2ω vs. fluence for L and XL sites.

Though large sites, in the L and XL categories, were shot below 12 J/cm^2, none of those sites showed any catastrophic growth. All the growth data, including no growth sites, is plotted in figure 7. Unlike the 3ω data shown in figure 6, no 2ω growth coefficient smaller than 0.05 was measuredd. Also of note in figure 7 is that several sites did not grow at all at fluences well above 12 J/cm^2.

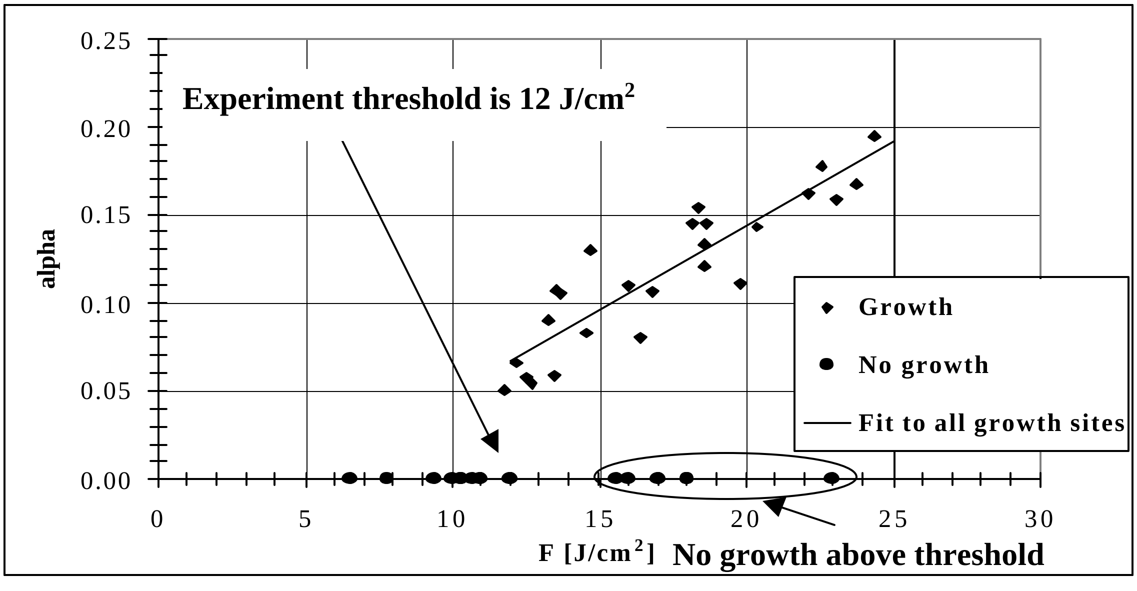


Figure 7. All 2ω growth coefficients including those sites that did not grow.

We undertook further exploration of the role of starting morphology as an aid in predicting the likelihood of site's potential for catastrophic growth. Higher resolution microscopy of fifteen sites enabled an additional parameter to be tracked; this was the typical size of an individual pit in the cluster of pits. The threshold for growth was found to be dependent on the starting morphology; sites of M & S designations did not grow at fluences below 19 J/cm^2. When the fluence was raised on two of these sites to 19 J/cm^2 they grew with growth coefficients that would be predicted from the linear fit shown in figure 7. Two sites with designations of XL3 and L3 did not grow at 12 and 17 J/cm^2, respectively. In both cases, we found that the individual pit sizes were approximately 30 µm. This data suggests that small sites have higher thresholds for growth. In addition, larger sites having small individual pit diameters require higher fluences for growth. A further observation relating to the observed 12 J/cm^2 growth threshold was that if a site has started its growth at a high fluence and then the fluence is lowered to 10 J/cm^2 growth continues on that site but with a slower growth rate.

Three heavily damaged sites were placed on the input surface where one was shot at 15 J/cm^2, one at 19 J/cm^2 and one at 22 J/cm^2. Only the latter site grew and its growth is plotted in figure 8.

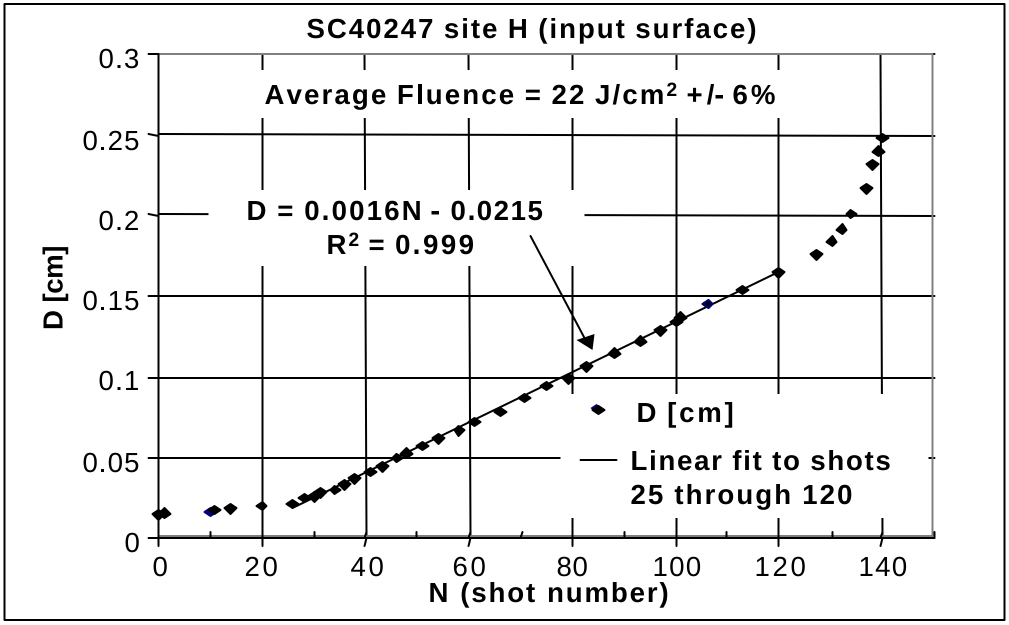


Figure 8. Growth of site located on input surface.

The linear fit to the data starts with shot 25 and goes out to shot 120, nearly 100 shots. This growth is not at all similar to that observed for damage located on the exit surface. Had this same site been positioned on the exit surface we would expect that only thirteen shots would have been required to grow the site to the same diameter. The other two sites did not change at all for 400 shots at the lower fluence. This limited data suggests that input surface damage has a higher threshold for growth and input sites grow more slowly than if the same site were located on the exit surface.

4. DISCUSSION

The measurements reported in this paper provide a database that can be used to predict the useful lifetime of a fused silica optic once one or more laser initiated damage sites are initiated during 2ω operation. Exponential growth occurs when the damage is located on the exit surface; thus, the lifetime of the optic can be severely impacted depending on the operating fluence. The experimental threshold of 12 J/cm^2 implies that for operation below this fluence one can expect that growth of laser damage sites will not limit the lifetime of the optic; many hundreds of shots should be possible before seeing any catastrophic growth. Our tests showed no growth for 300 to 400 shots. Above the experimental growth threshold, we have found that the magnitude of the exponential growth coefficient increases linearly with fluence.

Previous measurements[2] at 3ω have been compared to the current measurements. Both wavelengths show exponential increase in diameter with laser shot number at a fixed fluence. Growth at 3ω has a growth threshold of 5 J/cm^2; significantly lower than that measured at 2ω. There is a stronger dependence of the growth coefficient on fluence at 3ω.

Sites shot in vacuum had comparable growth rates to those shot in 10 torr of air. Sites initiated at 2ω grew comparably to those initiated at 3ω. If a site was located on the input surface, we found both a higher threshold and a linear dependence of the growth on shot number.

We looked at the initial damage morphology as an aid in predicting whether a site will grow. Both the overall starting size and the individual pit size was found to have a role in growth. The most notable effect is that the threshold for catastrophic growth is increased for small starting sizes and for large sites having small individual pits.

ACKNOWLEDGEMENTS

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