Preprint
UCRL-JC-144300

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This article was submitted to
33rd Annual Symposium on Optical Materials for High Power Lasers, Boulder, CO, October 1-3, 2001

U.S. Department of Energy

Lawrence Livermore National Laboratory

December 20, 2001

This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

UV Laser Conditioning for Reduction of 351-nm Damage Initiation in Fused Silica

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ABSTRACT

This paper describes the effect of 355-nm laser conditioning on the concentration of UV-laser-induced surface damage sites on large-aperture fused silica optics. We will show the effect of various 355-nm laser conditioning methodologies on the reduction of surface-damage initiation in fused silica samples that have varying qualities of polishing. With the best, generally available fused silica optic, we have demonstrated that 355-nm laser conditioning can achieve up to 10x reduction in surface damage initiation concentration in the fluence range of 10-14 J/cm^2 (355-nm @ 3 ns).

Keywords: UV laser surface damage, laser conditioning, damage initiation, fused silica

1. INTRODUCTION

The topic of laser damage at the 351-nm laser wavelength has generated interest in these proceedings for many years and is a topic which creates significant challenges to those that must produce and field optics on large aperture, high-peak-power lasers. Recently, our group has taken a somewhat novel approach to this issue by considering the laser damage issue to optics as a set of two coupled but distinct aspects. The first aspect is that of damage initiation and the second is that of the growth of initiated damage upon successive laser shots. It is the first aspect considered in this paper.

Historically, the study of laser damage has concerned itself with the laser damage threshold, which is to say the fluence at which the damage issue manifests itself. Much prior work has gone into understanding the phenomenon in order to increase the damage threshold such that damage issues will not manifest themselves in the laser fluence regime of interest. Our alternative view, based largely on the understanding of large-area damage statistics,[1] is to suppose that we cannot completely eliminate damage initiation, and what is really required is to make laser damage manageable. The most troublesome aspect of laser damage is that in many cases it grows over time in the fluence regimes that are of interest. Therefore, a workable strategy is to minimize the areal damage density during the initiation phase and then apply a growth mitigation treatment to limit the adverse effect of the laser damage once formed. Reduction of the laser damage density reduces the technical burden of applying growth mitigation strategies and is a desirable outcome.

One method that has been used with success in improving laser damage performance is that of laser conditioning. There are several reports in the literature describing the positive effects of laser conditioning on dielectric multilayer mirrors[2-5] The proposed mechanism for enhanced performance for multilayers is the gentle removal of nodule defects in the coatings which are prone to damage initiation. Since this sort of defect does not occur in bare fused silica optics, it is not clear that laser conditioning would be beneficial given the current understanding of how the process works. Laser conditioning has also been applied with success to increasing the damage resistance of bulk potassium dihydrogen phosphate (KDP) birefringent crystals.[6-10] However, it is not obvious from this prior work that laser conditioning would be effective at reducing the initiated damage density on the surface of bare crystalline or amorphous (fused silica) optics. An increase in the laser damage threshold

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for fused silica was reported by Kerr and Emmony by applying a so-called "laser annealing" technique. A fused silica sample was exposed to sub-damage threshold pulses from a 248-nm excimer laser before determining the damage threshold.[11] The wavelength and pulse duration (30 ns) of these tests are quite different from the wavelength and pulse length regimes under consideration here. Furthermore, there is no discussion of the extent to which the laser damage density is modified. Thus, we were encouraged to explore this issue more fully in this study. This paper discusses our experimental results in applying 355-nm laser conditioning to reduce the laser damage initiation density in bare fused silica.

2. EXPERIMENTAL DETAILS

Bare fused silica flat optics for testing were obtained from four different finishing vendors and had varying levels of quality. Table I summarizes the type and quality of the samples used in this study.

Table I
Types of samples used in the 355-nm laser conditioning study

Vendor ID	Quality	Finishing methods
1	Low – many visible damage precursors, scratches & digs	Conventional
2	High	Conventional
3	High	ZrO_x polish
4	High	Magnetorheological finish

The samples were treated with 355-nm laser pulses from the tripled Nd:YAG laser used in the LLNL Large Area Tester (LAT) laboratory. The LAT beam size is nominally 0.8 mm FWHM with a pulse duration of 7.5 ns and a repetition rate of 10 Hz; the LAT laser laboratory has been described in detail previously.[12] The laser fluence will be reported here in terms of the 3-ns equivalent fluence, using $\tau^{1/2}$ pulse length scaling. The sample is raster scanned with the laser beam using a 50% overlap between successive shots. Five different conditioning treatment regimens were used during this study. Table II shows the ramp in fluence for the conditioning raster scans and they are referred to sequentially as Conditioning Methodology "A" through Conditioning Methodology "E".

Table II
Conditioning methodologies used in the 355-nm laser conditioning study

Conditioning Methodology	Raster Scan Sequence
A	5 Raster Scans @ 8 J cm^{-2} (3ω @ 3ns)
B	5 Raster Scans @ 6 J cm^{-2} 5 Raster Scans @ 7 J cm^{-2} 5 Raster Scans @ 8 J cm^{-2}
C	5 Raster Scans @ 4 J cm^{-2} 5 Raster Scans @ 6 J cm^{-2} 5 Raster Scans @ 8 J cm^{-2}
D	5 Raster Scans @ 4 J cm^{-2} 5 Raster Scans @ 6 J cm^{-2} 5 Raster Scans @ 8 J cm^{-2} 1 Raster Scan @ 9 J cm^{-2}
E	3 Raster Scans @ 4 J cm^{-2} 3 Raster Scans @ 6 J cm^{-2} 3 Raster Scans @ 8 J cm^{-2}

After raster scanning the sample with the conditioning regimen, damage densities were obtained at 355 nm and fluences of 10 to 14 J cm^{-2} (scaled to 3-ns). The damage densities reported at fluences of 10 J cm^{-2} (3-ns scaled) and above take into account the total number of damage sites, including those produced during the conditioning sequence. The number of damage sites was determined using the LLNL Damage Mapping System; a CCD camera based image acquisition system designed to rapidly map the damaged surface of an optic.[13]

3. RESULTS AND DISCUSSION

Feit et al., have argued convincingly that the key factor which describes the damage behavior applicable to large area optics is the areal density of damage sites which are produced at a given fluence.[14] In addition, extrapolation to large areas requires scaling the results of small aperture laser damage testing using a Gaussian-to-flat top conversion formula. However, the purpose of this study is not to attempt to apply these results to large areas, but rather to internally compare the effects of different conditioning methodologies on different samples and finishing processes. Thus, the damage densities presented in the data below have not been scaled in the manner described by Feit et al.,[14] but are still comparable between tests. The data are pulse length scaled to 3 ns to remove confusion in that respect.

Figure 1 shows the effect of applying laser conditioning methodologies A through D to fused silica optic samples from Vendor 1. In the tests, several samples were used to check the effectiveness of the different treatment regimens as well as to test the effect of cleaning the sample before testing. Several points come to light. For samples of this type and from this vendor, there was no difference in the final damage density, regardless of the treatment regimen applied. After laser conditioning, each sample was left with a laser damage density of approximately 0.5 cm^{-2}. Therefore, we can conclude that the effect of starting the conditioning treatment at 8 J cm^{-2} is as effective as starting the treatment at 4 J cm^{-2}. The reduced damage density value of 0.5 cm^{-2} was achieved even without pre-cleaning of the surface. Simply exposing the sample to 12 J cm^{-2}, 3ω, 3ns laser light resulted in much higher damage densities. Cleaning the sample before damage testing reduces the damage density, but in all cases, laser conditioning further reduces the damage density by a factor of roughly two. The fact that there is no significant difference in the conditioning methodology on the outcome of the damage tests suggests that one can further refine the treatment regimen to reduce the number of raster scans and optimize the process to shorten the treatment cycle time.

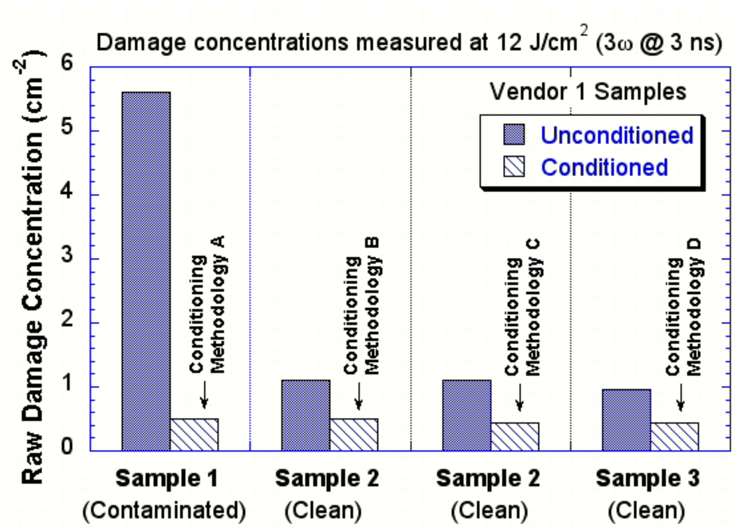

Figure 1. Plot of the damage density resulting from various laser conditioning treatments for several samples from Vendor 1.

Conditioning method "E" was then used throughout the rest of the testing as a reasonable compromise between starting the damage conditioning at a safe, low fluence level and shortening the numbers of scans with larger incremental increases in fluence to the final level needed to assure good damage performance at high fluences. Whereas samples from Vendor 1 were of rather low quality, we wanted to see what would happen if we conditioned samples considered to have good surface characteristics.

Figure 2 shows the effect of applying laser conditioning methodology "E" to samples from Vendor 2. Laser conditioning does not show an effect on the laser damage density until one exceeds about 10 J cm^{-2} in laser fluence. However, at that fluence, the effect is one of density reduction of about one order of magnitude.

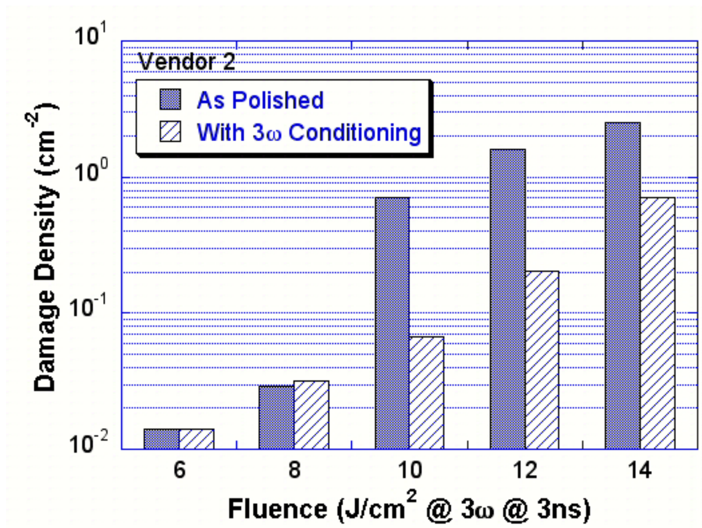

Figure 2. Damage density versus fluence for a Vendor 2 sample with and without laser conditioning. The treatment methodology was condition "E".

Vendor 3 also produced a high quality sample using zirconia as the polishing medium. Figure 3 presents the effects of laser conditioning, concentrating on the high fluence results. Vendor 3 produces a somewhat higher quality surface when comparing the "as polished" damage density values in figures 2 and 3. However, laser conditioning with methodology "E" still produces an order of magnitude lowering of the damage density at 10 J cm^{-2} laser fluence for this vendor's product.

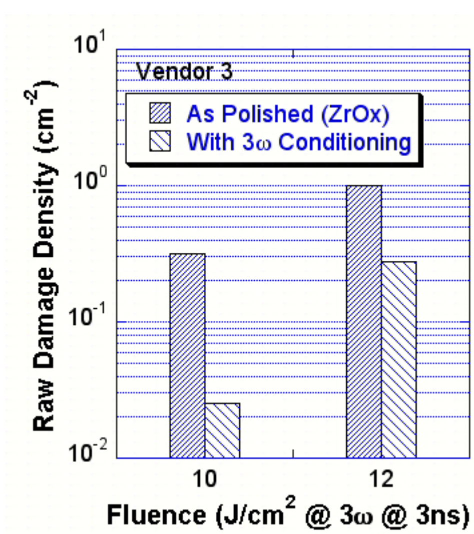

Figure 3. Plot of the damage density versus fluence for a sample from Vendor 3. Laser conditioning methodology "E" was used as the conditioning treatment.

We examined the effect of multiple treatments on a sample to see if there could be amplification of the improvement in damage density. Etching of silica surfaces has been attempted in the past to improve their laser damage tolerance.[15] Figure 4 compares the effect of HF etching (2 μm) and laser conditioning alone and combined by first etching the sample and then treating with laser conditioning methodology "E". Concentrating on the 12 J cm^{-2} fluence point, we see that etching has a small beneficial effect and laser conditioning has a larger beneficial effect. However, etching combined with laser conditioning shows a very large reduction in damage density. Density reductions of order 50X are achievable using the combined treatment regimen.

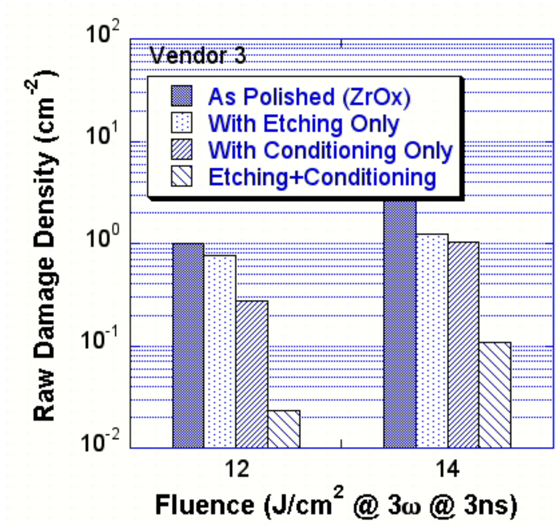

Figure 4. Plot of the damage density versus fluence for a Vendor 3 sample, comparing the effects of polishing, etching, laser conditioning and combining etching and laser conditioning.

The greatest reduction in laser damage density that we have observed to date comes from the combination of applying both etching and laser damage conditioning to samples prepared by finishing with a magnetorheological (MRF) technique.[16] Figure 5 plots the damage density for samples from Vendor 4 which compares results as finished, with etching and a combination of etching and laser conditioning.

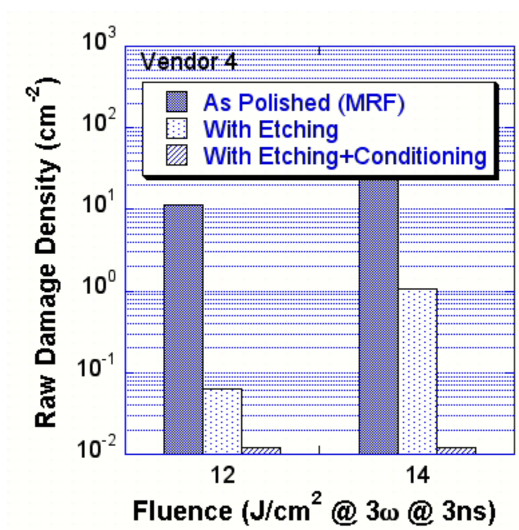

Figure 5. Plot of the damage density for samples from Vendor 4 with a surface finished by a magnetorheological technique.

As polished, the damage density of these samples exceeds that of the more conventionally finished samples. This result is likely due to the residual transition metal ($Fe^{2+/3+}$) impurities left by the MRF fabrication technique. Etching of the surface of these samples likely removes much of the impurities and results in a large decrease in damage density. However, the combined effects of both etching and laser conditioning results in ~ 100X decrease in damage density, even at the highest test fluence of 14 J cm^{-2}.

4. CONCLUSIONS

355-nm laser conditioning has shown great promise in reducing the density of damage sites in bare fused silica optics. The improvements are further enhanced when laser conditioning is combined with advanced finishing and surface treatment techniques, such as chemical etching and magnetorheological finishing.

5. ACKNOWLEDGEMENTS

Work performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract Number W-7405-ENG-48.

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