UCRL-JC-144293

CO_2-Laser Polishing for Reduction of 351-nm Surface Damage Initiation in Fused Silica

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This article was submitted to
Laser-Induced Damage in Optical Materials, Nov. 1-2, 2001
Boulder , CO.

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

November 1-2, 2001

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ABSTRACT

We have applied a carbon dioxide (CO_2) raster scanning laser polishing technique on two types of fused silica flat optics to determine the efficacy of CO_2-laser polishing as a method to increase the 351-nm laser damage resistance of optic surfaces. R-on-1 damage test results show that the fluence for any given 355-nm damage probability is 10-15 J/cm^2 higher (at 3 ns pulse length, scaled) for the CO_2-laser polished samples. Poor quality and good quality surfaces respond to the treatment such that their surface damage resistance is brought to approximately the same level. Surface stress and the resultant effect on wavefront quality remain key technology issues that would need to be addressed for a robust deployment.

Keywords: CO_2 laser polishing, raster scanning, surface damage, fused silica

1. INTRODUCTION

The modification of optic surfaces to improve their ability to withstand intense laser pulses is a well established area of investigation. One method of surface treatment which has been reported previously, with some interesting results, consists of exposing the surface of optics to a carbon dioxide (CO_2) laser beam.[1-4] In these past studies, the emphasis was on the laser damage threshold modification at 1.06 µm wavelength after surface treatment. The consensus in these studies was that improvements in the laser damage threshold could be obtained, albeit with some other problems associated with effects on optics properties, such as stress and surface figure. There was no mention of the effect of a large area CO_2-laser treatment on laser damage properties at UV wavelengths in these prior references. One previous study did in fact examine the effect of large aperture CO_2-laser treatment of fused silica with some damage testing done at 351-nm.[5] However, the results of that study were inconclusive as to whether CO_2-laser processing was able to affect a reliable, positive change in the damage threshold under UV illumination.

In a companion paper in these proceedings, we report on the effect of treating laser damage sites with single pulses of a CO_2-laser to mitigate the growth of those sites upon further laser irradiation. Our emphasis has been to view damage from a different perspective in that we consider it separable into two aspects, one of damage initiation and the other of damage growth. We were compelled to re-examine the issue of mitigation of laser damage with full aperture exposure of fused silica optics to a CO_2-laser beam given the results in our companion study.

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2. EXPERIMENTAL DETAILS

Flat fused silica optics, 50 mm in diameter, from two finishing vendors were used in these experiments. Samples from Vendor A possessed a medium grade of surface quality and were finished via a conventional polishing process. Vendor B, an alternate vendor, supplied samples that were of rather low quality in that they contained many visible damage precursors, such as scratches and pits. These samples were also conventionally polished. The samples were placed on a computer-controlled stage and exposed to a stationary CO_2-laser beam with an approximately Gaussian profile with a $1/e^2$ radius of about 20 mm. The CO_2-laser used was a 1 kW continuous wave Rofin-Sinar RS-1000.

The scan pattern of the CO_2-laser beam is shown in Figure 1. The scan rate was set to 250 cm/min. The initial CO_2-laser power setting was 50 W. The power was increased by 25 W after each scan loop, up to some maximum power. In one case, the maximum power was 900 W. At the highest power setting of 900 W, the passage of the CO_2-laser beam was clearly visible as a bright-red-to-white spot moving over the surface of the sample. We refer to this condition as "heavy polishing". Unless otherwise noted, this was the condition used to get most of the data shown in the next section. In another case, the maximum power was only 750 W. At the highest power setting of 750 W, the passage of the CO_2-laser beam was visible as a dull red spot moving over the surface of the sample, as viewed in a darkened room. We refer to this condition as "light polishing". In each case, the highest power was sustained for about 10 minutes. The sample was then cooled slowly by decreasing the CO_2-laser power by 10 W after each loop.

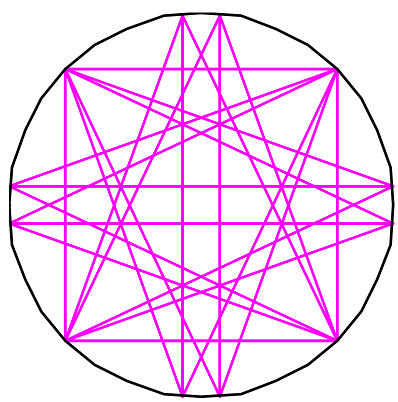

Figure 1. Scan pattern for CO_2-laser polishing. Scan rate = 250 cm/min.

After processing surfaces with the CO_2-laser beam, the samples were laser damage tested in the Small Optics Test facility at LLNL. This facility uses a tripled Nd:YAG laser beam at 355 nm with a nominal 0.8 mm beam diameter FWHM, 7.5 ns pulse duration and a pulse repetition frequency of 10 Hz. Laser damage testing consisted of a series of tests in which the fluence was ramped-up on a given site until failure (i.e. damage); this is the so-called "R-on-1" test. The test was repeated on a number of sites to form a cumulative damage probability curve.[6] All results were scaled to 3 ns using a $\tau^{1/2}$ relationship.

3. RESULTS AND DISCUSSION

It is a well established fact that there are differences in the laser damage threshold when considering damage that occurs to front and rear surfaces of a bare (un-coated) optic. Generally speaking, electric field enhancement by Fresnel reflections cause the rear surfaces to damage before the front surface, thus the rear surface appears to have a lower resistance to laser damage.[7] We took this into account when accumulating data to form the cumulative damage probability curves. Figure 2 shows the result of testing a sample from Vendor A without any laser polishing treatment.

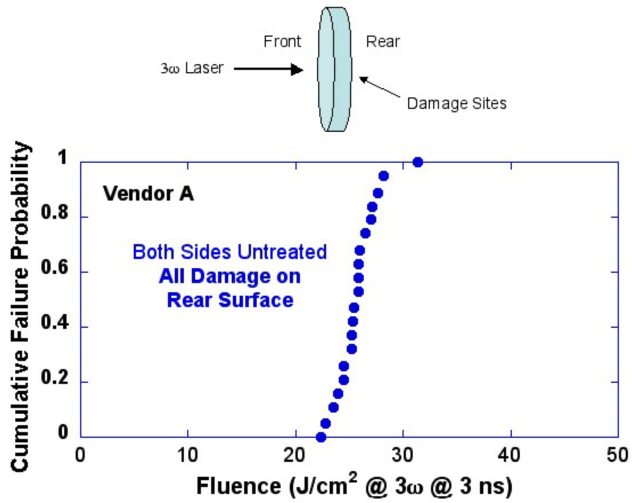

Figure 2. Plot of the failure probability for an untreated optic from Vendor A. All of the laser damage occurs on the rear surface.

All of the laser damage occurs on the rear surface, which is consistent with anecdotal and published[7] optic behavior in this type of test. Figure 3 illustrates what happens to the cumulative failure probability when one surface of this optic is CO_2-laser polished and that surface is used as the output surface in the laser damage test.

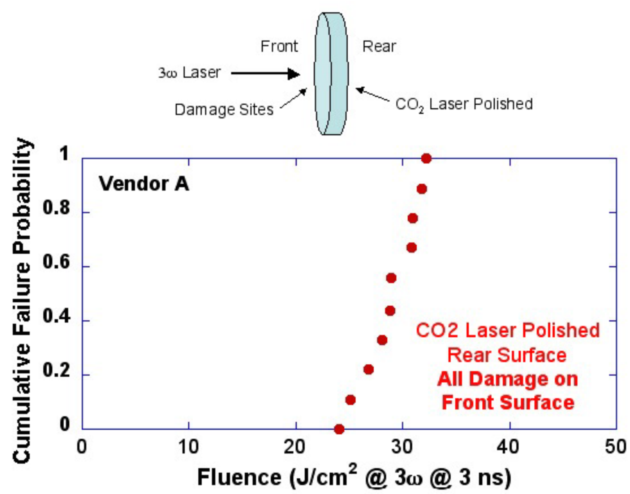

Figure 3. Failure probability as a function of fluence level with one side CO_2-laser polished and placed in the output surface configuration.

The slope of the failure probability line is slightly less than the untreated case, but the interesting point to note is that all of the damage now occurs on the front surface. The fact that no laser damage occurs on the rear surface is strong evidence for the very positive effect of laser polishing on the damage resistance of surfaces. Also, the failure probability curve in Figure 3 is best able to describe the intrinsic damage resistance of a native surface, unmodified by issues associated with field enhancements and other non-linear effects. This is because the CO_2-laser polishing treatment has rendered the rear surface effectively impervious to laser damage.

When the laser polished surface is tested as the input surface, simply by inverting the sample, the failure probability curve shown in Figure 4 shifts strongly to lower fluences. Note that all of the damage spots now occur on the rear surface. Intuitively, one might guess that the result of this test would be the simple reproduction of the curve in Figure 2, before any polishing treatment. However, the result is well beyond the errors in the testing and suggests that CO_2-laser polishing is affecting the surface in a manner which amplifies those processes within the glass which strongly contribute to the rear surface damage resistance, such as the beam contrast induced by front surface ripples.

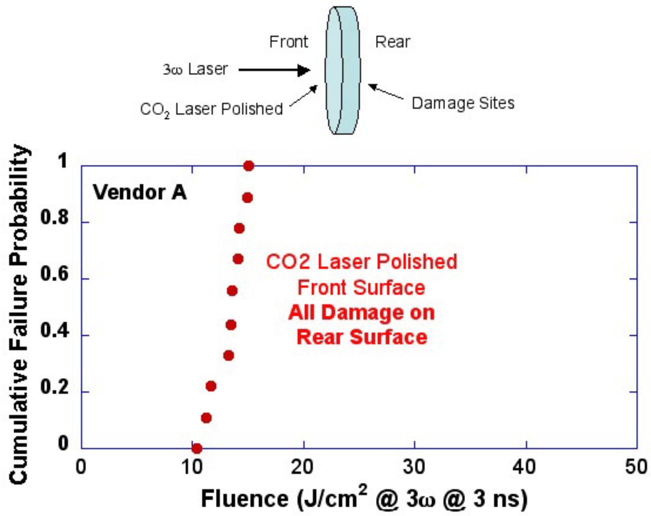

Figure 4. Plot of the failure probability versus fluence for the same sample used to collect the data for Figure 3, except the laser polished surface has been shifted to the input side of the test apparatus.

When both sides of an optic are CO_2-laser polished, the failure probability behaves in the manner shown in Figure 5. At lower fluences, it is the rear surface damage that dominates the failure. However, as the fluence is increased, contributions from both the front and the rear come into play. The failure probability curve is still very well defined and the damage resistance of the part is much improved over the case where the part is untreated.

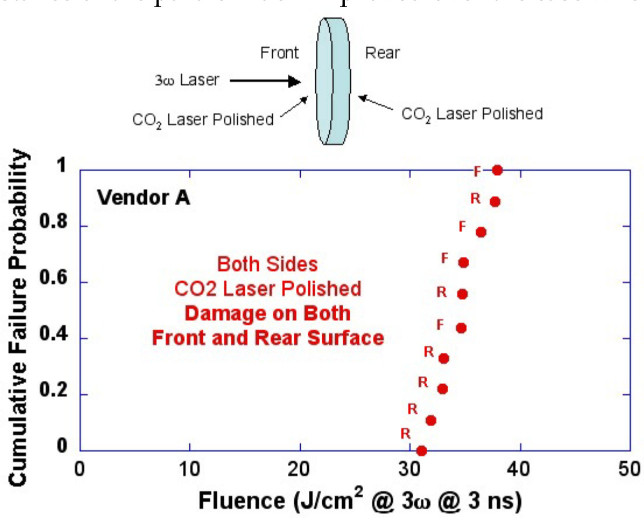

Figure 5. Plot of the failure probability versus fluence for a sample in which both surfaces have been CO_2-laser polished.

The tests so far described have been on samples which were of relatively good quality. We wanted to check the effect on a poorer quality sample and Figure 6 illustrates the result. Even when the original quality of the surface of the optic is poor, CO_2-laser polishing increases the damage resistance to a level comparable to that for a better quality surface. In fact, the high end of the probability curve extends to even higher fluences than seen for the higher quality sample; compare with Figure 5.

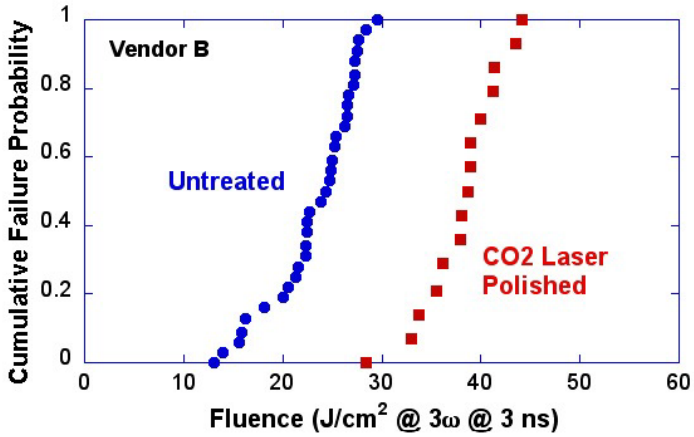

Figure 6. Plot of the cumulative failure probability for a Vendor B derived sample surface, both untreated and CO_2-laser polished. The output surface is the surface which had been laser polished.

In order to investigate the effect of the level of CO_2 polishing treatment, samples from Vendor A sample were treated with a the "heavy" and the "light" polishing regimen and subsequently damage tested. As shown in Figure 7, the "heavy" and "light" treatment processes brought the samples to the same level of resistance to 355-nm damage.

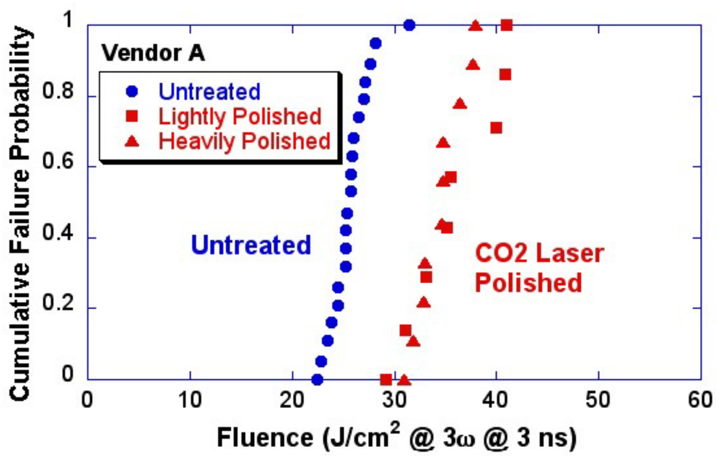

Figure 7. Plot of the cumulative failure probability versus fluence for surfaces treated with both the "heavy" and "light" treatment process (see experimental details section for further explanation).

Historically, one limitation to implementation of this type of technology has been the accumulation of undesirable residual stress in the optics after CO_2-laser treatment and loss of surface flatness. We also have observed this effect in a qualitative manner. There are also deleterious effects on the wavefront quality which would also need to be addressed. While we have discovered that a "light" treatment can provide the same effect as a "heavy" exposure to CO_2-laser light, we have not discovered the absolute minimal amount of treatment that could satisfy all of the stress, wavefront and damage resistance enhancement requirements.

4. CONCLUSIONS

We have shown that CO_2-laser polishing can strongly increase the damage resistance of a fused silica optic surface at the 355-nm wavelength. The level of improvement has been demonstrated over a range of initial surface qualities, both poor and good. Polished surfaces always outperform unpolished surfaces, regardless of orientation in the test apparatus. CO_2 polishing, to the extent tested in this study introduces a level of stress and laser beam wavefront perturbations which continue to be technology barriers for full deployment into the optics processing mainstream.

5. ACKNOWLDEGEMENTS

The authors would like to gratefully acknowledge the technical assistance of Walter Grundler in setting up and performing the laser polishing tests. 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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