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INTRINSIC-DAMAGE-THRESHOLD STUDY

MASTER

Final Report

for the period ending

15 November 1979

PAUL A. TEMPLE

June 1982

Work Performed Under Contract

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NAVAL WEAPONS CENTER

China Lake, CA 93555

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Prepared for the

U.S. DEPARTMENT OF ENERGY

DIVISION OF ENERGY TECHNOLOGY

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Boulder, Colorado, 30-31 October 1979

CO_2-LASER POLISHING OF FUSED SILICA SURFACES FOR INCREASED LASER DAMAGE RESISTANCE AT 1.06 μm*

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We have prepared bare fused silica surfaces by subjecting the mechanically polished surface to a rastered cw CO_2 laser beam. Analysis shows that this processing causes (a) removal of a uniform layer of fused silica and (b) a probable re-fusing or healing of existing subsurface fractures. The fused silica removal rate is found to be a function of the laser intensity and scan rate. These surfaces are seen to have very low scatter and to be very smooth. In addition, they have exhibited entrance surface damage thresholds at 1.06 μm and 1 nsec, which are substantially above those seen on the mechanically polished surface. When damage does occur, it tends to be at a few isolated points rather than the general uniform damage seen on the mechanically polished part. In addition to the damage results, we will discuss an observational technique used for viewing these surfaces which employs dark-field illumination.

Key words: Fused silica; laser damage; surface finishing; surface polishing.

Introduction

We have prepared fused silica surfaces by subjecting the mechanically polished surface to a cw CO_2 laser beam treatment. These surfaces are found to exhibit increased laser damage resistance to 1.06 μm, 1 nsec pulses. In addition to a description of the damage results, we will discuss some of the other physical properties of surfaces prepared in this way.

Surface Preparation

All the samples used in this set of measurements were Suprasil II, polished by Zygo Corporation. They were quite smooth with a Talystep rms roughness of under 10 Å. Figure 1 shows the setup used to treat these mechanically polished surfaces with a CO_2 laser beam. Since the wavelength of CO_2 radiation is much longer than the wavelength of the absorption edge of fused silica, CO_2 radiation is highly absorbed by fused silica. The result is intense local heating of the fused silica surface. Thus far only unfocused CO_2 radiation from a Coherent Radiation Model 41 laser has been used. By using a beam power of approximately 75 watts and a scan rate of ~ 5 mm/sec, we have succeeded in achieving the desired result of modifying the fused silica properties without seriously degrading the figure of the surface. At this power and scan rate, the region under irradiation appears as a bright reddish-white spot about 2 to 3 mm in diameter. At higher laser powers or slower scan rates, sublimed SiO_2 is seen to come off the irradiated region and is redeposited as a white powder on the cooler parts of the sample just above the irradiated region. By scanning in a left-to-right motion and by beginning the scans on the lower part of the sample and making each successive scan 0.5 mm above the previous scan, this fine white powder is reevaporated, and the finished part does not have SiO_2 powder on the laser-polished portion.

* Work sponsored by Navy Independent Research funds and Department of Energy.

Surface Inspection

The techniques used to inspect the surfaces prepared in this study have been Nomarski microscopy and total internal reflection microscopy (TIRM) [1,2][1]. The latter technique has been described elsewhere and in a poster paper at this meeting [3]. In TIRM the transparent part is illuminated from within with a laser beam (fig. 2) at an angle just greater than the critical angle. Since total reflection occurs, no light escapes except where there has been some perturbation of the surface. The image seen through the microscope, then, is one of a dark background with bright regions where the surface has been disturbed.

Damage Results

Six samples prepared by CO_2-laser polishing have been damage tested at Lawrence Livermore Laboratory. These have all been front surface tests at a wavelength of 1.06 μm and a pulse length of 1 nsec. Damage is defined as the appearance of pits as seen in Nomarski microscopy. In general, the results have indicated that these surfaces exhibit a higher resistance to damage than do conventionally polished fused silica. This is evidenced by no pits appearing at energy density levels which would normally cause damage on a conventional part and fewer individual pits when damage finally does occur at higher energy density levels. Table 1 is a list of the results from two samples. Keeping in mind that typical polishing samples have a damage threshold which ranges from 10 to 20 J/cm^2, the laser-polished samples show a very high resistance to damage.

Table 1. Fused silica entrance surface damage.

Sample		J/cm^2	Comments
Z1-23		30.6	No light, 1 site
		40.7	Flash, 3 sites
		55.5	Flash, 3 sites
Z1-21		33.4	Flash, no damage
		23.0	Flash, minor damage
		40.1	Flash, minor damage
	Same site	29.0	Flash, no damage
	Same site	38.0	Flash, no damage
	Same site	42.3	Flash, damage

Of particular interest are the three shots on one site where the first two shots caused no damage.

Damage Morphology

Figure 3 is a set of three photographs taken of a conventionally polished fused silica surface which has been damaged on the entrance surface by a 15 J/cm^2 pulse. The typical dished-out damage pits are seen in the Nomarski photograph, while the TIRM photograph shows a great deal of structure unrelated to the occurrence of damage. The simultaneous photograph in the center shows that most of the damage pits do indeed have a small bright spot in the center, but certainly damage is more easily detected by Nomarski inspection.

Figure 4 shows Nomarski and TIRM photographs of a damage site on laser-polished fused silica. Here, while much damage is visible in the TIRM photo, only one pit is visible in the Nomarski photograph. As will be pointed out below, the surface was virtually featureless prior to damage. The pit, in addition, does not have the usual conical shape as seen on conventionally polished parts. Rather, it is quite sharp-edged. While it seems quite certain that the damage resistance of laser-polished fused silica is substantially better than conventionally polished fused silica, it is possible that damage may have taken place which went undetected by Nomarski microscopy but which would have been visible in TIRM if that technique had been visible during the damage tests.

[1] Figures in brackets indicate the literature references at the end of this paper.

Physical Properties of Laser-Polished Fused Silica

Shown in figure 5 are two TIRM views of a fused silica surface as seen before and after laser polishing. From these photos it is seen there are residual marks on the mechanically polished part due to the mechanical polishing process, and that these are no longer seen in the laser-polished surface. As indicated in the figure, this particular part was initially very smooth, and, at least in the short run, laser polishing did not degrade this smoothness. Shown in figure 6 are two TIRM views of a fused silica surface similar to that in figure 5 but after one-half-hour etch in 5% HF acid at room temperature. The absence of any linear features in the laser-polished surface indicates that, at least on the surface, it has "forgotten" its past experience of being mechanically polished. While not shown, these two surfaces reveal similar information in Nomarski microscopy. That is, the mechanically polished surface is quite highly decorated with scratches, while the laser-polished surface is quite uniform in appearance.

Figure 7 shows two Zygo interferograms of a fused silica part which has been laser polished by scanning at successively slower rates on widely separated regions. The figure on the left is the result of interference between the polished surface and a standard flat. In this case, changes in the interference pattern are exclusively due to changes in the surface profile. This figure indicates that the regions which have been laser polished are depressed below the mean surface. We have verified that this is so by Talystep measurements. In the case of the part shown in figure 7, the pass which resulted in a featureless appearance in TIRM had a measured maximum depression of 1500 Å. All passes with less depression still showed the marks characteristic of polishing, while those CO_2 scans which were made at a slower rate showed ever wider featureless regions.

The photo on the right of figure 7 was made by placing a second fused silica blank in contact with the laser-polished surface of the first sample. The inner region was filled with a fluid of index identical to that of fused silica. The existence of the fringe distortion coincident with the laser-polished scan lines indicates that the index of the material in the laser-polished region has increased. This is possible since the specific gravity of SiO_2 can range over a value of from 2.2 to 2.66, and the index ranges over a value of 1.46 to 1.55, depending upon the crystalline state. Fused silica is, in addition, a fairly open lattice material, and it may be collapsing to a more dense form under laser irradiation.

Mechanical tests on the surfaces of laser-polished parts indicate that these surfaces are under tensile stress. Surface tensile stress is expected to result from this type of rapid heating and cooling of the surface of a cool substrate. However, tensile stress would also result if the surface was indeed going to a more dense phase, as is suggested by the data in figure 7.

Damage Resistance

CO_2-laser-polished parts appear, by etching as shown in figure 6, to have fewer defects associated with mechanical damage from previous processing. This may be the reason for the increased damage resistance of laser-polished parts. Even in the case of laser-polished parts, however, it is quite possible that deeper, unhealed regions are the sites of subsequent damage, if the part is subjected to a sufficiently high photon flux during damage testing. Figure 8 shows a damage site which is suggestive of this. Here, a laser-polished region has been damaged. Both the TIRM and Nomarski photographs show a linear feature and damage along this feature.

Most damage sites do not reveal any particular linear pattern. In the usual mechanically polished surface there is literally a mat of scratches and fractures, and it is not surprising to see damage occurring in an essentially random fashion. Laser-polished parts, on the other hand, appear to have a much reduced surface microcrack density, and the laser flux required to cause damage to these deeper and less numerous defects is much higher, as shown in table 1.

Real Optics

The question of making useful optical components from CO_2-laser-polished parts will depend upon one's ability to retain optical figure during CO_2-laser polishing. This is not unlike the situation which exists for flame-polished or acid-etched surfaces, both of which can show higher damage resistance than the mechanically polished surface. In the case of CO_2-laser polishing, however, the situation is more easily controlled. In addition, it appears as though a sufficient CO_2 polish to improve the damage threshold may not disrupt the figure too badly.

Conclusion

In this paper we have presented a method for the preparation of fused silica surfaces which results in increased surface damage resistance to 1.06 μm radiation. These surfaces are prepared by intense heating of the fused silica surface by an incident cw CO_2 laser beam. The resulting surface is essentially featureless, as seen in dark-field microscopy. Evidence was shown to suggest that many of the microscopic fractures present after mechanical polishing are removed by this polishing technique. The simultaneous removal of mechanical defects and increase in damage threshold was taken as evidence that surface fractures play a role in lowering the damage threshold of polished glass surfaces. Finally, we have noted that in its present state CO_2-laser polishing results in a degraded surface figure, but that it appears as though surface figure could be retained with careful CO_2-laser processing.

References

[1] Temple, P. A., "An Improved Dark-Field-Like Surface Inspection Technique Using Total Internal Reflection," presented at Conference on Optics '79, 23-25 May 1979, Los Alamos, New Mexico.

[2] Temple, P. A., "Total Internal Reflection Microscopy: A Surface Inspection Technique," submitted to Appl. Opt.

[3] Temple, P. A., "Examination of Laser Damage Sites on Transparent Surfaces and Films Using Total Internal Reflection Microscopy," this conference.

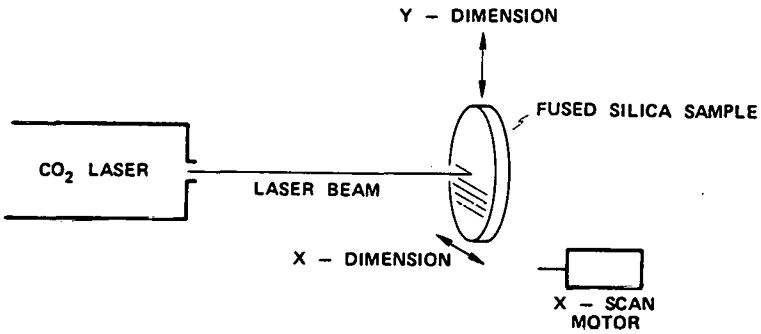


Figure 1. CO_2-laser-polishing apparatus. The laser is an unfocused Coherent Radiation Model 41 CO_2 laser. The sample is 3 meters from the laser. The sample is moved left and right by a variable speed motor and up and down by hand. The sample was unheated and in air during polishing.

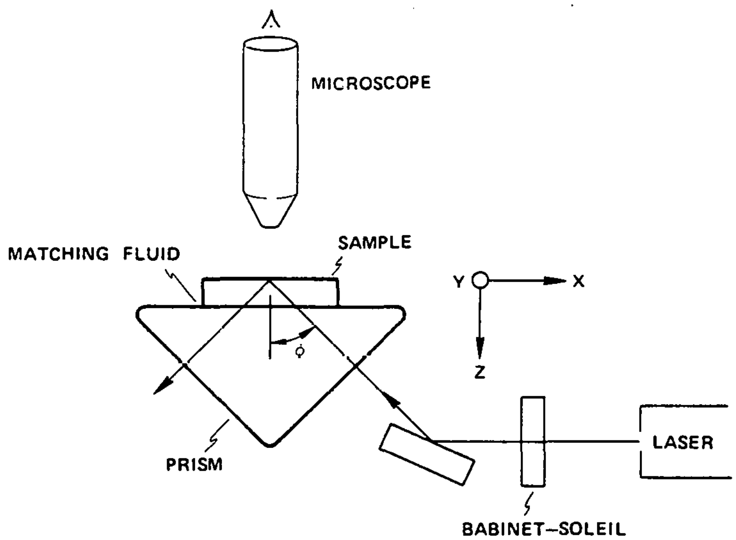


Figure 2. The total internal reflection microscopy (TIRM) used to inspect highly polished transparent samples. A polarized laser beam is coupled into the sample by a prism. The angle of incidence at the sample top surface is just beyond the critical angle. The sample is gripped by a microscope slide manipulator, and, since the sample is supported on an oil film on the prism, it can easily be moved about for inspection of the entire upper surface. The microscope used for the photographs in other figures was a Zeiss Nomarski microscope with the Nomarski illuminator turned off.

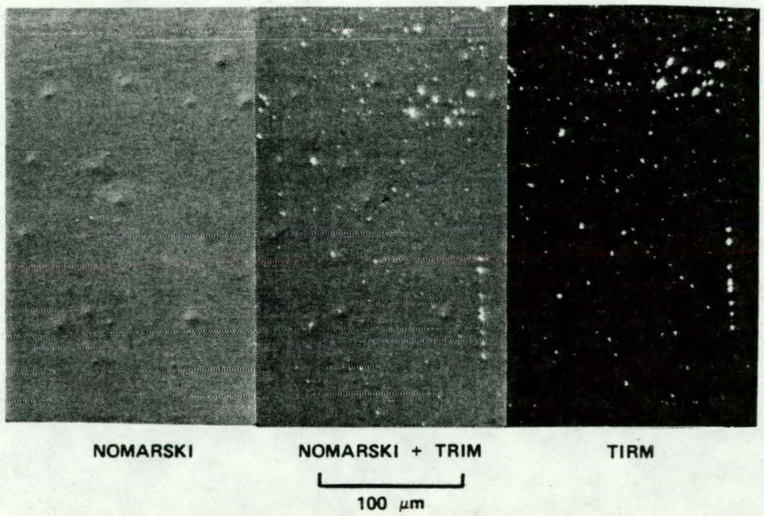


Figure 3. Three photos of the same region of a laser-damaged, conventionally polished piece of fused silica. The view on the left is a Nomarski photo showing several pits caused by a 15-J/cm^2, 1.06-μm wavelength, 1-nsec pulse length exposure. The photo on the right is a TIRM view. Since the part is mechanically polished, it has many features visible in this view which are not related to the damage shown in the left photo. The center view shows the Nomarski and TIRM illuminations simultaneously. It can be seen here that few of the TIRM features are actually identified with damage sites. Most of these features are mechanical damage due to the polishing process.

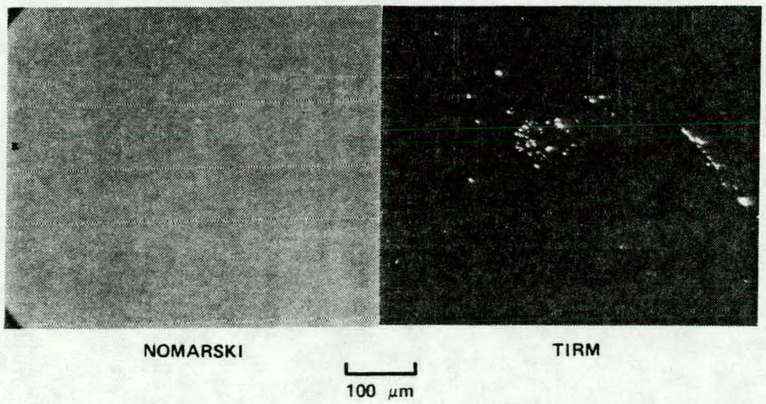
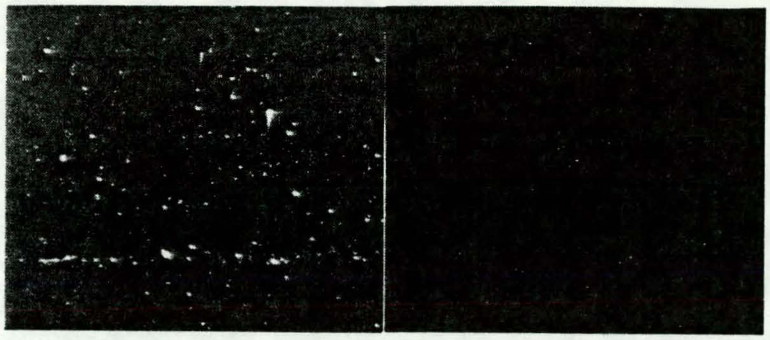


Figure 4. A Nomarski and TIRM view of the same damage site on a laser-polished surface. The laser-polished site was featureless before damage, and any features seen in the TIRM view are the result of damage, either as actual pits or as debris. Note that the damage is not easily detected on the Nomarski photograph.

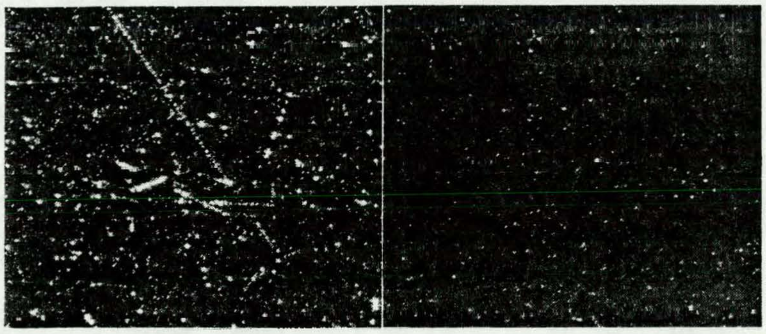


OUTSIDE CO_2 POLISHED REGION
ROUGHNESS 3.3 Å rms

INSIDE CO_2 POLISHED REGION
ROUGHNESS 2.7 Å rms

100 μm

Figure 5. A piece of fused silica before and after laser polish. This part is unusually featureless even as a mechanically polished part. The laser-polished part is totally featureless in both TIRM and Nomarski illumination.



OUTSIDE CO_2 POLISHED REGION

INSIDE CO_2 POLISHED REGION

AFTER 1/2 HR 5% HF ETCH

100 μm

Figure 6. Two regions of the same fused silica sample as seen in TIRM after one-half hour of etching in 5% HF acid. The linear features, evident in the mechanically polished part, are totally lacking in the laser-polished part.

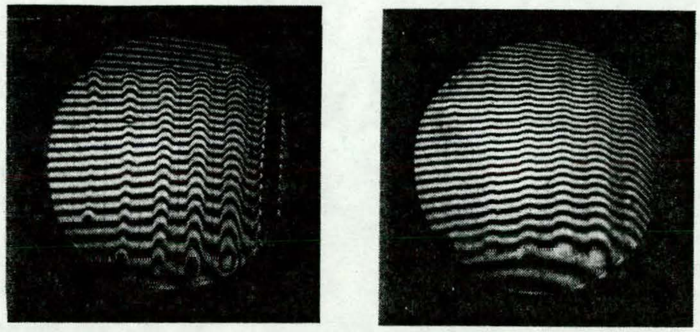


Figure 7. Two Zygo interferograms of a fused silica part which has been laser polished by six passes, evenly spaced, over the surface of the part. The scan rates were successively slower for scans nearer the right. The photo on the left demonstrates that there has been a reduction in the height of the surface where the surface was scanned. Talystep measurements verified this to be the case. The photo on the right shows that the material in the laser-polished region is of different optical density than the rest of the sample as a result of laser polishing in that region.

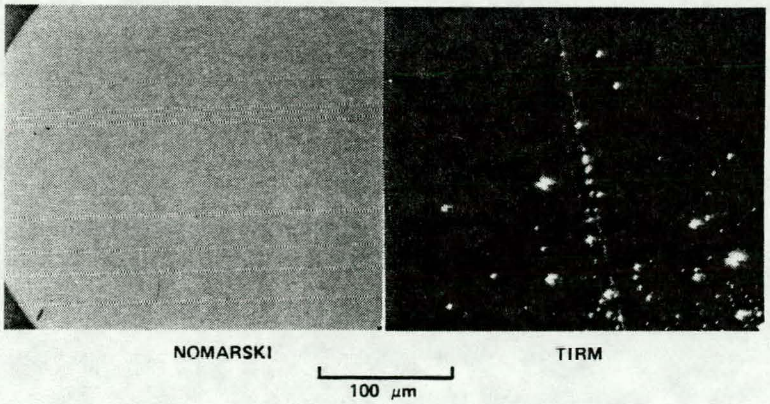


Figure 8. A Nomarski and TIRM view of a damaged region on a previously featureless laser-polished part. Of particular interest is the linear feature along which damage occurred. This is suggestive of that linear feature, probably a scratch introduced much earlier in the mechanical polish, being the nucleation site for damage.