Research Article

Full Aperture CO₂ Laser Process to Improve Laser Damage Resistance of Fused Silica Optical Surface

Wei Liao, Chuanchao Zhang, Xiaofen Sun, Lijuan Zhang, and Xiaodong Yuan

Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang 621900, China

Correspondence should be addressed to Xiaodong Yuan; yxd66my@163.com

Received 28 February 2014; Accepted 26 May 2014; Published 17 July 2014

Academic Editor: Xiao-Tao Zu

Copyright © 2014 Wei Liao et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

An improved method is presented to scan the full-aperture optical surface rapidly by using galvanometer steering mirrors. In contrast to the previous studies, the scanning velocity is faster by several orders of magnitude. The velocity is chosen to allow little thermodeposition thus providing small and uniform residual stress. An appropriate power density is set to obtain a lower processing temperature. The proper parameters can help to prevent optical surface from fracturing during operation at high laser flux. S-on-1 damage test results show that the damage threshold of scanned area is approximately 40% higher than that of untreated area.

1. Introduction

A large number of fused silica optics are installed during the construction of high power solid laser facility [1], such as national ignition facility (NIF) and laser MegaJoule (LMJ) which were both used to drive the inertial confinement fusion (ICF). Fused silica material is used because of its theoretically excellent performance in optical transmittance, thermodynamic characteristic, and especially the damage resistance [2]. But in the process of actual application, even though the flux density is far below their intrinsic damage threshold [3, 4], laser-induced damage (LID) still frequently occurs, especially for the optics installed in the third-harmonic section.

For the fused silica optics, lots of researches indicate that carbon dioxide (CO₂) laser treatment is an effective mean to mitigate the problem of laser damage. One of the most common ways is to mitigate the damage site by melting or evaporation, thus avoiding their catastrophic growth under subsequent laser irradiation [5, 6]. But as early as 1979, Temple et al. [7] had proposed an idea to polish fused silica optics by CO₂ laser for improving the damage resistance at 1064 nm. In 2001, Brusasco et al. [8] continued this research to find out whether the damage initiation at 351 nm could also be reduced by CO₂ laser polishing. Their researches demonstrated that CO₂ laser polishing could significantly

improve the damage resistance of fused silica optics both at 1064 and at 351 nm. However, no matter how the process parameters are optimized, polishing will always lead to the surface topography destruction and residual stress, which need to be well controlled.

This work presents a modified processing strategy to suppress the negative effects induced by laser polishing. In contrast to the previous works, a galvanometer is set up instead of electric translation stages to control the relative movement between optics and laser beam. This could greatly increase the scanning speed so that the temperature field becomes more homogeneous than before [5]. In order to balance the demand of damage resistance improvement with those negative effects mentioned above, different treatment parameters are investigated and several testing methods such as atomic force microscope (AFM) are used in this paper. Meanwhile, the damage resistance is characterized by the S-on-1 method [9] which is one of the most important methods for laser-induced damage threshold (LIDT) testing at 355 nm.

2. Experiment

2.1. Optical Path. The CO₂ laser beam with the wave length 10.6 μm , as shown in Figure 1, was expanded before transferring into the galvanometric scanning system. The orientation of laser beam was changed by the scanning mirrors driven

FIGURE 1: Schematic diagram of the optical path.

by galvanometers. Consequently, the irradiated position of sample surface could be easily controlled. Field lens was used to focus the laser beam and ensure a flat focal plane even in the off-axis position.

The galvanometric scanning system is produced by RAY-LASE Inc. and the specification is SS-HS-LD-30. When a field lens with a focal length of 163 mm is used, the full scanning speed of this system is 7 m/s, the minimum line interval is 1 μm, and the scanning range is more than 100 mm. The focal length of field lens used in this optical path is 250 mm. A GEM-100L CO₂ laser is produced by Coherent Inc., which could output the quasi-continuous laser with a repetition frequency of 20 kHz. The power of CO₂ laser can be adjusted from 0 to 100 W.

2.2. Sample Preparation. UV grade synthetic amorphous silicon dioxide, corning 7980, with dimensions of 40 × 40 × 5 mm³ were used. In order to remove contamination and deposition layer, samples were etched by buffered hydrofluoric acid (HF: 2%, NH₄F: 11%) for one minute [10]. As shown in Figure 2, each sample was divided into three areas and the middle area was treated as a reference.

2.3. Experimental Process and Testing. A rapid raster scanning mode was adopted to polish the samples. The scanning velocity and line interval were set as 6 m/s and 1 μm, respectively, under an assumption that the focal length of field lens was 163 mm. Actually, focus position for the optics system used in this paper was about 242 mm from the field lens. During raster scanning, samples were placed at various distances from the field lens so that the power density could be regulated by the change of laser spot size on the surface of sample. In this work, three typical distances were taken into account, that is, 248 mm, 249 mm, and 250 mm. Besides,

FIGURE 2: Sample size and region division method.

for comparison purposes, each part of samples was scanned twice with some certain parameters.

Transmission wave front, surface roughness, and residual stress induced by different treating parameters were tested to evaluate the ability of this new polishing method to control the side-effects. The LIDT of samples is determined by the typical S-on-1 laser damage tests. The laser is a Nd:YAG laser operated at 355 nm with pulse width of 7 ns and a near-Gaussian beam profile. During the damage threshold testing, laser beam was focused to 0.36 mm² at the sample plane. At last, in this paper, the emphasis is on the comparison and results are discussed between treated and untreated area rather than the absolute value.

FIGURE 3: Interferometer images of (a) samples polished in distance of 248 and 249 mm, (b) samples polished in distance of 249 and 250 mm twice.

3. Results and Discussion

3.1. Transmission of Wave Front. Figure 3(a) shows that the upper part of the sample was polished at the distance of 248 mm while the lower part was at 249 mm. After polishing by CO_2 laser, the value of wave front distortion (WFD) is visibly increased, which is from approximate 20 nm of middle area to 61 nm of lower section and 125 nm of upper section, respectively. It indicates that surface is severely destroyed as demonstrated by the previous works. But when the distance of sample was adjusted to 250 mm, that is, a lower power density, a smaller WFD value was obtained. As shown in Figure 3(b), the upper section was polished twice at the distance of 249 mm while the lower section was at the distance of 250 mm. WFD value is 60 nm for upper area and 23 nm for lower area, respectively, and the latter is comparable to the untreated middle area. These results indicate that the surface can be maintained by this new polishing method as long as the power density is low enough.

Additionally, as shown in Figure 3, the WFD is usually distributed in the center of the samples. It may be because of the poor heat dissipation performance of the center. To resolve this problem, driving the galvanometer by the sinusoidal current is a viable way.

3.2. Surface Roughness. To determine whether the samples are exactly polished in such a lower power density, the

surface roughness is detected by AFM. Figure 4(a) gives a typical surface topography of the samples, which is etched by buffered hydrofluoric acid, with a 25.226 nm PV value of roughness (PVVR). Remarkably, Figure 4(b) shows that after being polished at the distance of 250 mm, PVVR of the sample is reduced to 5.167 nm. The surface of polished sample is become smoother under low power density, which indicates that the surface is melted slightly without apparent destruction to the surface shape.

3.3. Residual Stress. Rapid cooling after being melted is often accompanied by the generation of residual thermal stress. In order to contrast the difference between this improved polishing method and the previous ones [7, 8], a repetitive experiment was conducted and the residual stress was tested. When the Senarmont method is used for the measurement of residual stress, the optical path difference (OPD) is about 9 nm for the previous methods. However, as shown in Figure 5, residual stress of the samples polished by the new method is hardly detectable. This result is expected and indicates that high speed can help to form a more uniform temperature field and to reduce the heating depth. So the residual stress can be well controlled.

3.4. Damage Resistance. The polishing method would be meaningless if the damage resistance is not improved.

FIGURE 4: Atomic force microscope images of (a) untreated area and (b) the area which was polished at distance of 250 mm.

FIGURE 5: Polariscope images (sample A was polished at the distance of 248 mm and 249 mm; sample B was polished at the distance of 249 mm and 250 mm).

FIGURE 6: LIDTs curve.

According to the testing results of LIDT, shown in Figure 6, no matter which parameter is used, the damage resistance is improved to different degree. In this case, the areas polished at 250 mm are worth special attention. Firstly, enhancement of 0% damage probability threshold means that the number of defects is reduced by the treatment. In other words, certain

defects can be removed by this new polishing method. Secondly, enhancement of 100% damage probability threshold indicates that this new polishing method may also change the surface structure of fused silica.

Through these works, there must be an optimal parameter combination which was effective for improving the damage resistance of fused silica optics while keeping their original state simultaneously. But the reason for this improvement is still uncertain. The possible mechanism includes three aspects: firstly, some defects might be eliminated because of laser annealing [11]; secondly, microstructure of the surface might be changed, such as the passivation of dangling bonds or the change of distance between atoms [12]; at last, the surface might be strengthened due to the compressive stress like the laser peening of metal [13]. In the future, systematical experiment will be carried out for confirming the exact mechanism.

4. Conclusion

An improved method of CO₂ laser polishing is represented in this paper. After being polished, the damage resistance of a fused silica optic surface at 355 nm wavelength was obviously increased. The side-effects such as destruction of surface shape and residual stress are also well controlled after the optimization of processing parameters. For the further application of this method, more methods to describe the microstructure changes are needed for understanding its physical mechanism. Furthermore, the residual stress existing in subsurface must be tested precisely for evaluating the mechanical properties of the polished surface.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

- [1] J. H. Campbell, R. A. Hawley-Fedder, C. J. Stolz et al., "NIF optical materials and fabrication technologies: An overview," in

Optical Engineering at the Lawrence Livermore National Laboratory II: The National Ignition Facility, Proceedings of SPIE, pp. 84–101, January 2004.

- [2] A. K. Burnham, L. Hackel, P. Wegner et al., “Improving 351 nm damage performance of large-aperture fused silica and DKDP optics,” Preprint UCRL-JC-144298, Lawrence Livermore National Laboratory, 2002.
- [3] H. Bercegol, P. Bouchut, L. Lemaître, B. Le Garrec, and G. Razé, “The impact of laser damage on the lifetime of optical components in fusion lasers,” in *Laser-Induced Damage in Optical Materials*, vol. 5273 of *Proceedings of SPIE*, pp. 312–324, September 2003.
- [4] A. K. Burnham, L. Hackel, P. Wegner et al., “Improving 351 nm damage performance of large-aperture fused silica and DKDP optics,” Preprint UCRL-JC-144298, Lawrence Livermore National Laboratory, 2002.
- [5] I. L. Bass, G. M. Guss, M. J. Nostrand, and P. J. Wegner, “An improved method of mitigating laser induced surface damage growth in fused silica using a rastered, pulsed CO₂ laser,” in *Laser-Induced Damage in Optical Materials*, Proceedings of SPIE, September 2010.
- [6] J. J. Adams, M. Bolourchi, J. D. Bude, G. M. Guss, M. J. Matthews, and M. C. Nostrand, “Results of applying a non-evaporative mitigation technique to laser-initiated surface damage on fused-silica,” in *Laser-Induced Damage in Optical Materials*, vol. 7842 of *Proceedings of SPIE*, September 2010.
- [7] P. A. Temple, D. Milam, and W. H. Lowdermilk, “CO₂ laser polishing of fused silica surfaces for increased damage resistance at 1.06 μm ,” *National Bureau of Standards Special Publication*, vol. 568, pp. 229–236, 1979.
- [8] R. M. Brusasco, B. M. Penetrante, J. E. Peterson, and S. M. Maricle, “CO₂-laser polishing for reduction of 351-nm surface damage initiation in fused silica,” UCRL JC-144293, Lawrence Livermore National Laboratory, 2001.
- [9] J. Becher and A. Bernhardt, “ISO-11254: an international standard for the determination of the laser-induced damage threshold,” *Proceedings of SPIE*, vol. 2114, pp. 703–713, 1994.
- [10] L. Wong, T. Suratwala, M. D. Feit, P. E. Miller, and R. Steele, “The effect of HF/NH₄F etching on the morphology of surface fractures on fused silica,” *Journal of Non-Crystalline Solids*, vol. 355, no. 13, pp. 797–810, 2009.
- [11] N. Shen, P. E. Miller, J. D. Bude et al., “Thermal annealing of laser damage precursors on fused silica surfaces,” *Optical Engineering*, vol. 51, no. 12, Article ID 121817, 2012.
- [12] M. A. Stevens-Kalceff and J. Wong, “Distribution of defects induced in fused silica by ultraviolet laser pulses before and after treatment with a CO₂ laser,” *Journal of Applied Physics*, vol. 97, no. 11, Article ID 113519, 2005.
- [13] L. A. Hackel and H. L. Chen, “Laser peening—a processing tool to strengthen metals or alloys to improve fatigue lifetime and retard stress-induced corrosion cracking,” UCRL ID-155327, Lawrence Livermore National Laboratory, 2003.