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Comparison of anti-reflective coated and uncoated surfaces figured by pitch-polishing and magneto-rheological processes

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ABSTRACT

When completed, the National Ignition Facility (NIF) will provide laser energies in the Mega-joule range. Successful pulse amplification to these extremely high levels requires that all small optics, found earlier in the beamline, have stringent surface and laser fluence requirements. In addition, they must operate reliably for 30 years constituting hundreds of thousands of shots. As part of the first four beamlines, spherical and aspherical lenses were required for the beam relaying telescopes. The magneto-rheological technique allows for faster and more accurate finishing of aspheres. The spherical and aspherical lenses were final figured using both conventional-pitch polishing processes for high quality laser optics and the magneto-rheological finishing process. The purpose of this paper is to compare the surface properties between these two finishing processes. Some lenses were set aside from production for evaluation. The surface roughness in the mid-frequency range was measured and the scatter was studied. Laser damage testing at 1064 nm (3-ns pulse width) was performed on surfaces in both the uncoated and coated condition.

Keywords: Laser damage, polishing, lenses, surface roughness

1. INTRODUCTION

The National Ignition Facility (NIF) is a project funded through the Department of Energy. The NIF is designed to be a 192-beam, 1.8 MJ experimental laser facility. This unique facility will create environments of extreme pressures and temperatures for experiments conducted in support of the national security, energy, and basic science communities. The conventional part of the NIF building was completed in 2001. By the end of March, 2003, the first four beam lines will be able to transport light from the injection laser system (ILS), through the main beam lines, and into the target chamber.

There are approximately 8700 high performance laser optics in the ILS.[1] These optics have stringent wavefront and surface roughness requirements, as the large spatial period errors in the optics will affect the beam size. A relay telescope is included in the ILS to adjust for a portion of these aberrations. The smaller spatial period errors of the optics will be blocked by a spatial filter in the main laser system. This leaves the spatial periods of interest which are specified by the wavefront gradient and surface roughness. Wavefront errors must remain less than 63 nm peak-to-valley, 21 nm rms, and 21 nm rms/cm gradient. Surface roughnesses must be less than 0.8 nm rms for spatial periods less than 2 mm. The effect of increased wavefront gradients and roughnesses is to increase the amplitude modulation of the laser beam.

The ILS has about 550 aspheric lenses in the baseline optical configuration.[2] Fortunately the departure from a best-fit sphere is on the order of microns, a surface that is amenable to the magneto-rheological finishing (MRF) process. This process is commercially available as a computer-controlled optical finishing tool, and installed in many lens fabrication suppliers. One of the project's concerns with the MRF process is that an iron compound makes up a large fraction of the polishing slurry. The MRF process may leave residual iron contaminants on a surface which are difficult to removed by pre-coat cleaning steps. These contaminants could degrade the laser damage thresholds of the lenses and raise the operational cost of the ILS. Another question is whether a lens surface treated with the MRF process will satisfy the gradient and surface roughness requirements in the spatial periods of interest. Surface roughness will be addressed in this paper along with laser damage thresholds by comparing lenses that have been final figured by a conventional pitch-polish and a MRF process. The surfaces were examined before and after the deposition of an anti-reflective coating.

2. EXPERIMENTAL

2.1 Sample preparation

An optical component supplier fabricated a batch of lenses for a 4-element beam line telescope. The elements were made from fused silica with birefringence, bubbles and inhomogeniety specified as 0/5, 1/6x0.04 and 2/4;5 in ISO 10110 notation, respectively.[3] Three of the four elements were spherical lenses and the fourth was an aspherical lens. The fabricators for the bid proposals were specifically selected for their capabilities in aspheric lens fabrication with the magneto-rheological finishing (MRF) process. As part of the manufacturing process, the selected supplier applied the MRF process even on spherical surfaces. Two of these lenses were randomly selected as samples for this study.

The lenses in this study were conventionally pitched-polished on both surfaces. On one side of each lens, the surface was final-figured with the MRF process. The supplier set their MRF process to remove material to about a micron of depth. The lenses were masked such that on half of the clear aperture was deposited with an anti-reflective (AR) coating designed for a center wavelength of 1053 nm. The coating was applied with a reactive e-beam deposition process for a high laser damage threshold AR.[4] Figure 1 shows the spectral characteristics of the two coatings on sample 10810004. The scans were taken with a micro-gonio-reflectometer that took the scans on the curved lens surfaces, and not of witness samples. The AR coating on the conventionally pitch-polished surface is more centered than the coating on the MRF surface. The pitch-polished surface of this bi-convex sample is flatter (Side 1 Radius = 2000 mm) than the MRF surface (Side 2 Radius = 112 mm). The steepness of the short radius may account for some of the de-centering observed on the AR coating deposited on the MRF surface.

The four available surface conditions on each test lens consist of an uncoated pitch-polished surface, an uncoated MRF surface, and a coated pitch-polished surface and a coated MRF surface. The laser damage thresholds, surface roughness (0.08 to 2 mm spatial period range), and darkfield microscopy pictures were taken of these surfaces for comparison.

2.2 Surface Roughness

Surface roughness was measured with a Veeco NT2000 system. This is a white light phase measuring interferometer located at LLNL.[5] The data from the surface roughness test is filtered with an software application developed in-house[6] that analyzes for spatial periods from 0.080 to 2.0 mm. The measurement was performed using a field-of-view (FOV) of no less than 6 mm x 6 mm (11 mm x 11mm maximum). The 6 mm x 6 mm FOV was obtained on the NT2000 with its FOV setting at 0.5 and the 1.5x objective in place. The pixel size is about 11.8 microns at these settings. The system has been shown to resolve spatial periods as small as 30 microns.

2.3 Laser Damage Test

A laser damage test procedure was developed and tailored specifically for the evaluation of components for the special needs of the NIF small optics program.[7] Since the beam footprints typically comprise a large fraction of the optical clear aperture, a significant portion of the test aperture is exposed to the test laser beam. By irradiating a large area, it is assured that preferential damage sites, which can be randomly located in the coated sample, are located and exposed. Usually, a typical scan at a given fluence consists of over 2000 sites. Another unique requirement of the procedure is the overlap of the laser test beam and that the same area be tested for the next higher fluence level. This part of the procedure simulates the laser conditioning effect that the optical coatings would experience in practice. Lastly, a probable threshold is established which allows for a more marginal laser damage of the optic. The test procedure has produced results that correlate with testing performed at LLNL and other laser damage test service facilities.[8]

Figure 2 is a sketch of the laser damage test set-up. The irradiation source used in the damage tests is a commercial Nd:YAG laser system providing up to 500 mJ of laser energy in a 3.5 ns pulse width. The laser operates at a pulserepeat frequency (PRF) of 10 Hz, with a >90 % fit to Gaussian beam profile in the far field. The laser energy is varied at the sample plane by using a half waveplate and thin film polarizer. The beam was focused using a telescope to provide a spot size on the far field on the order of 1 mm ($1/e^2$) diameter.

Laser beam diagnostics include pulsewidth, energy, and beam profile measurement. The pulsewidth is measured by observing the leakage through a 45° high reflecting mirror. An ultra-fast oscilloscope and detector with risetime < 200 ps is used to perform these measurements. The laser power is measured using a calibrated pickoff mirror and calorimeter. The beam profile is observed by placing a pickoff in the focused beam at near normal incidence. The profiling system is then positioned at the equivalent distance from the telescope to target.

Scanning the optic in the laser beam is performed using a set of motorized translation stages. The velocity of the stages is determined by the beam diameter at the target plane and the PRF of the test laser. The velocity is programmed to provide an overlap between pulses at the 90% energy level. By scanning at these levels the complete region is irradiated using the central or "peak" region of the Gaussian beam.

Laser induced changes to the optical surface are characterized by a high resolution vidicon camera equipped with a macro focusing lens. The camera is positioned such that the vidicon was observing the surface of the optic at a nominal magnification of 50x. The camera is equipped with a filter to reduce the infrared response and avoid observation of the 1064 nm pump beam. The camera is interfaced to a monitor and VCR to allow a videotape record of the irradiation procedure. A 5 mW Helium–Neon laser is aligned to overlap the damage beam at the target surface. The visible beam enhances the surface scatter and laser damage site formation allowing easy observation on a television monitor.

The Qualified, Probable, and Failed damage thresholds on each surface condition of the lens was determined. The definitions of Qualified, Probable, and Failed damage thresholds are the following:

> The Qualified damage threshold means that up to the specified fluence, the optic showed no signs of damage.
>
> The Probable damage threshold means that at the specified fluence one or more of the following occurs;
> 1. change in the scatter above the noise limit and verified to be damage by microscopy,
> 2. visible pinpoint damage observed by the operator which is less than 100 μm, does not grow, and occurs in less than 1% of the sites.
>
> The Failed damage threshold means that at the specified fluence, one or more of the following occurs
> 1. pinpoint damage at more than 1% of the sites,
> 2. pinpoint damage larger than 100 μm or,
> 3. damage which indicates growth upon further illumination (considered to be catastrophic damage).

The fluence is increased in increments of 3 J/cm^2 per area scan, and the measurement error in the power is +/- 1 J, pulse-width is 3.5 +/- 0.5 ns, and spot size is 1.15 +/- 0.05 mm.

3. RESULTS

3.1 Darkfield Microscopy

The darkfield microscopy pictures of the four surface conditions are in Figure 3. Comparing the uncoated surfaces, the pitch-polished surface has noticeably lower density of surface artifacts. One likely explanation for the increased density is that the MRF process removes the re-hydrolyzed fused silica layer, uncovering defects from previous polishing and/or shape generation steps.[9] After coating, the defects are larger and much easier to observe because the defects act as seeds for nodular growth during the evaporation.[10]

3.2 Surface Roughness

The surface roughnesses for each of the four process conditions are summarized in Table 1. Not all of the surfaces could be measured for roughnesses because of the steep radii. The statistical error in the roughness data is indicated by those surfaces where four sites were measured on the same side of a lens. The pitch-polished surfaces are smoother than the MRF surfaces in the mid-spatial period range of 0.08 mm to 2.0 mm. The rougher surfaces may be caused by the contact size of the MRF media on the work piece. The MRF contact spot is on the same order of magnitude of the spatial period of interest.[11] In the final-figuring of the lens, the deposition of an AR coating does not appear to add significant roughness to a surface. This was expected because AR coatings are thin and their typical columnar growth pattern have geometric dimensions much smaller than the spatial periods of interest.

Figure 4 shows the false-color maps of surface roughness from the coated pitch-polished and MRF surfaces. The topographical scale bars are different in the panels a and b. The concentric rings in pitch-polished panel is probably fresnel fringing contributions from the second surface. The scale bar of the MRF surface is from −16.3 to 6.2 nm. There appears to be some bands going from 2 o'clock to 8 o'clock in the topography. Both the coating vendor, under high intensity illumination, and laser damage test facility, using a microscope, were able to note a distinct quality differences between the two surfaces during their sample cleaning. Cleaning did not visibly alter the features.

Table 1 Surface roughness (rms nm) in the spatial period range from 0.080 mm to 2 mm. The standard deviation is given when four sites were tested on the same surface.

Pitch-polished surfaces	MRF surfaces
Uncoated Sample10810004	Uncoated Sample10830003
0.40	1.68
Coated Sample10810004	Coated Sample10830003
0.34	2.02
Coated Sample10830003	Coated Sample10810004
0.56 +/- 0.05	4.02 +/-1.78

3.3 Laser damage threshold

The four surface conditions on sample 10810004 were laser-damage tested. Prior to testing, the surfaces were cleaned with an acetone wipe. For the testing of these surfaces, the high powered laser beam enters the side opposite the test surface. Although the surfaces are curved, the dimensions of damage on the output surface are reasonably close to the irradiation dimensions on the input surface. No adjustment of the laser fluences were made to compensate for lensing. The three laser damage threshold levels are presented in Table 2. In the uncoated tests, the surface damaged at existing defect sites and failed catastrophically. The lower density of defect sites on the pitch-polished surface may be the reason for slightly higher damage thresholds. The MRF surfaces generated a high laser damage threshold (1064 nm) in spite of the fact that the process uses a polish media with an absorbing material, carbonyl iron.[12] The damage thresholds of the coated surface were identical. The increased scatter counts due laser damage was nearly the same between the coated pitch-polished and MFR surfaces. The damage threshold of this fused silica lens was more affected by the deposition of an anti-reflective coating than either of the two polishing process used in final figuring the lens.

Table 2 Laser damage thresholds (1064 nm, 3.5 ns pulsewidths) of four surface conditions. Fluences are tested to within ± 3 J/cm^2.

Damage Level	Uncoated Pitch-Polished	Uncoated MRF	Coated Pitch-polished	Coated MRF
Qualified	38	35	11	11
Probable	Not Applicable	Not Applicable	14	14
Failed	41	38	17	17

4. SUMMARY

Fused silica lenses were fabricated in a commercial setting by using conventional pitch-polishing and magnetorheological finishing processes for high fluence laser lenses. The surfaces of uncoated and coated lenses were compared for surface quality and laser damage thresholds at 1064 nm. The pitch-polished surfaces had better surface quality than the MRF surfaces. The scatter defect density was lower. The surface roughness is lower by a factor of at least 4x in the spatial period range from 0.08 mm to 2.0 mm. In spite of the lower surface quality and the use of an iron compound in the polishing media, there was no significant difference in laser damage thresholds of these uncoated and coated surfaces. Further roughness testing is being conducted to determine if the roughness between the two processes converges at smaller spatial periods. Optimization of the MRF process with each supplier is a possible method to improve the surface quality of these surfaces.

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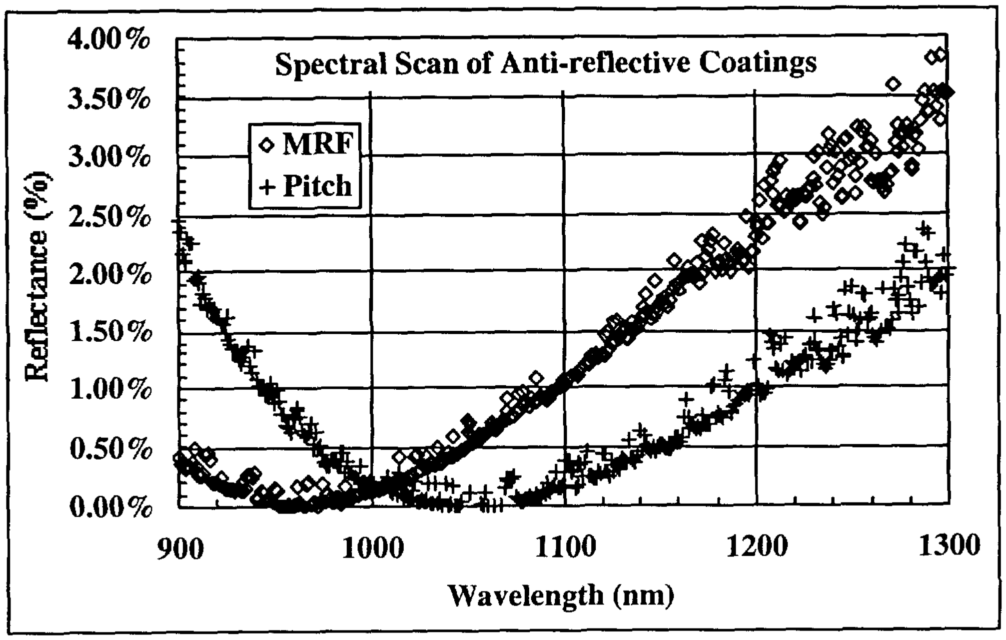

Figure 1 Spectral scans of the coated surfaces. The coatings are centered adequately for laser damage testing at 1064 nm.

Figure 2 Laser damage test set-up

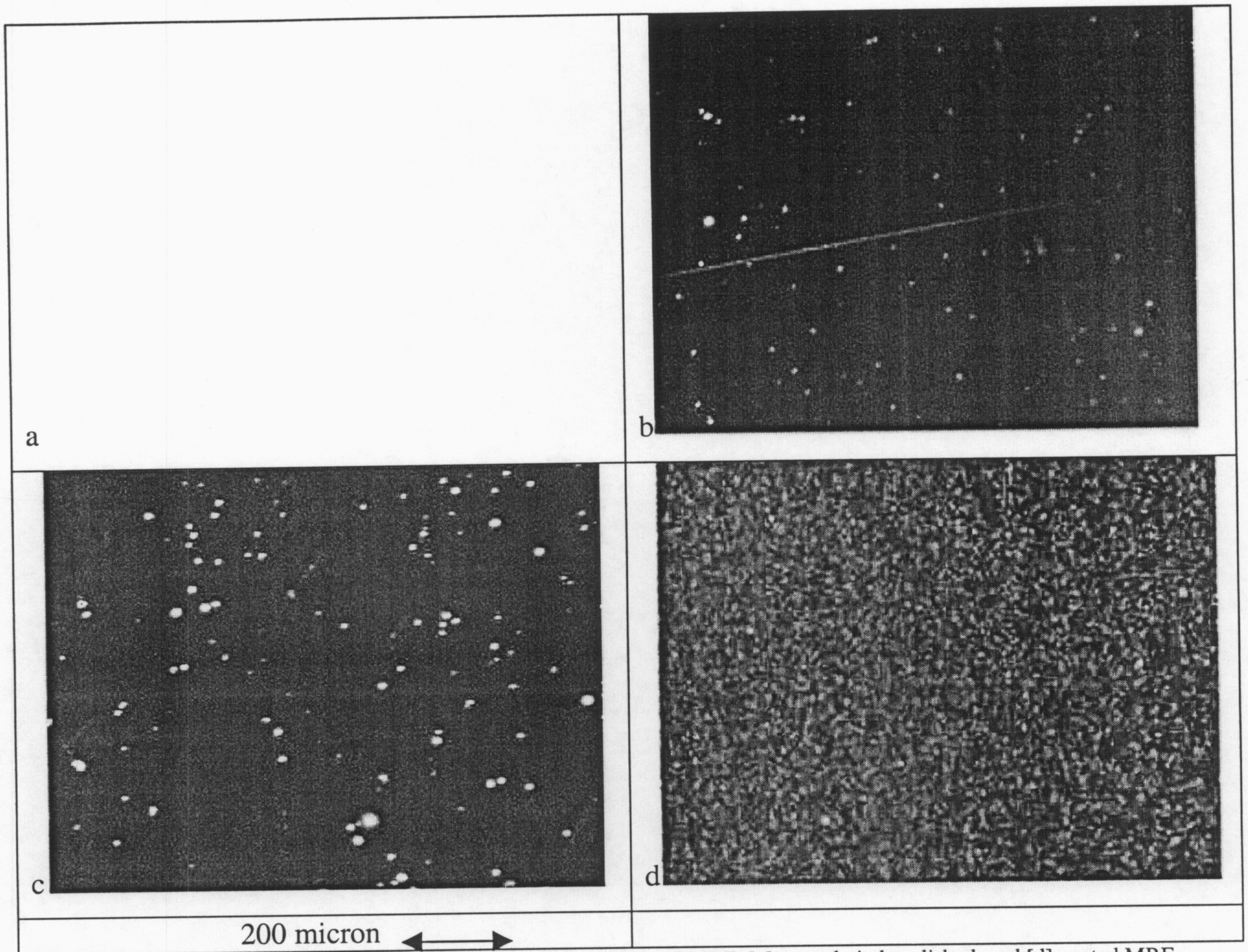

Figure 3 Scatter sites in the [a] uncoated, pitch-polished, [b] uncoated MRF, [c] coated pitch-polished, and [d] coated MRF surfaces.

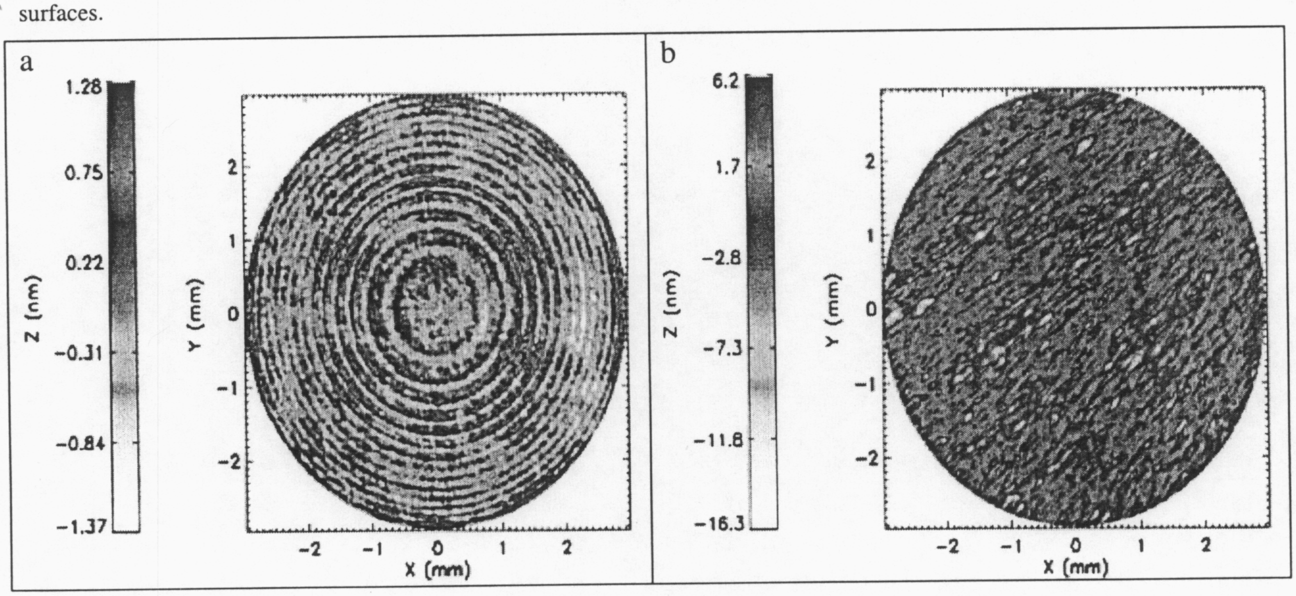

Figure 4 Roughness maps of the coated surfaces after filtering between 0.080 mm to 2.0 mm. Note the change in height bar. Each field-of-view is 6 mm diameter.