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ABSTRACT

In many high energy laser systems, optics with HMDS sol gel antireflective coatings are placed in close proximity to each other making them particularly susceptible to certain types of strong optical interactions. During the coating process, halo shaped coating flaws develop around surface digs and particles. Depending on the shape and size of the flaw, the extent of laser light intensity modulation and consequent probability of damaging downstream optics may increase significantly. To prevent these defects from causing damage, a coating flaw removal tool was developed that deploys a spot of decane with a syringe and dissolves away the coating flaw. The residual liquid is evacuated leaving an uncoated circular spot approximately 1mm in diameter. The resulting uncoated region causes little light intensity modulation and thus has a low probability of causing damage in optics downstream from the mitigated flaw site.

Keywords: coating flaw, mitigation, HMDS sol gel, laser modulation, laser damage

1. INTRODUCTION

The National Ignition Facility (NIF) employs a set of final optics on the target chamber for beam shaping, frequency conversion, focusing, diagnostic sampling, and debris protection of each of its 192 beams. Prior to entering the target chamber, each laser pulse passes through a continuous phase plate (CPP), a polarization rotator (PR), a second harmonic generator (SHG), a third harmonic generator (THG), an off-axis wedged focusing lens (oWFL), and a grating debris shield (GDS). In this final optic arrangement, the PR, SHG and THG are made from Potassium Dihydrogen Phosphate (KDP) or Potassium Dideuterium Phosphate (DKDP).[1] Crystal optics of this type have an antireflective coating composed of Hexamethyldisiloxane (HMDS) treated sol. During the coating process, imperfections on the surface of the optic can generate coating flaws in the sol. These coating flaws have the potential to spatially modulate the transmitted laser pulse and damage downstream optics. Because of the high value of final optics on NIF, a coating flaw removal tool was developed to remove these light modulating defects.

2. FLAW IDENTIFICATION AND CHARACTERIZATION STATION

In dip and spin coating of sols, the suspended solids tend to distribute non-uniformly around surface irregularities during drying. Most problematic are surface-bound contaminant particles which hold an inordinate (relative to the nominal liquid coating thickness) volume of coating fluid due to capillary action. During drying, most of the solids in the localized capillary reservoir eventually migrate some distance away from the precursor region (particle, dig, etc.) and accumulate in surface deposits many times thicker than the nominal far field coating. The most common form of dried coating flaw is a crescent or ring shape resulting from the simultaneous outward radial transport of solids toward the inward moving drying front. As Figure 1 shows, coating flaws of this type do not generally cause surface laser damage, but they can produce laser light intensification after a propagation distance of several centimeters with the potential to cause damage on downstream optics.

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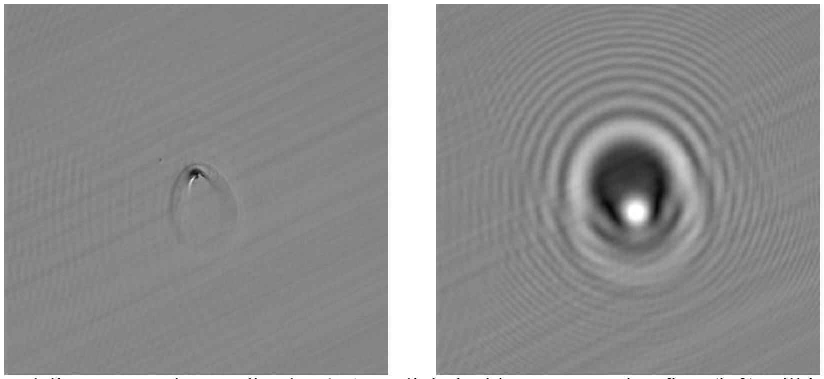

Figure 1a. Computer modeling was used to predict that 351-nm light incident on a coating flaw (left) will intensify (right) after propagating 4 cm.

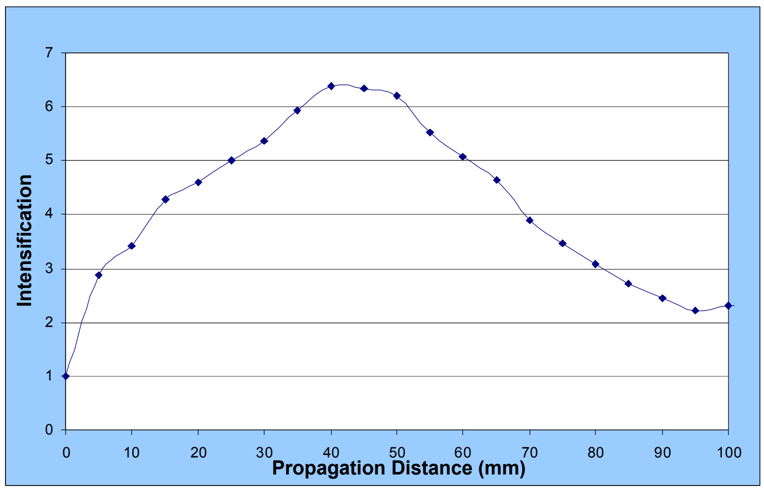

Figure 1b. Graph of peak intensification as a function of propagation distance away from the coating flaw shown above; if another optic were paced between 30 and 60 mm away from the flaw, it would have a high probability of damaging.

Because of the difficulty of finishing and cleaning KDP and DKDP optics, surfaces often contain a large number of precursors that lead to coating flaws. Coating flaws may modulate and cause downstream damage, depending on the size, shape and surface of the generated coating flaw. Because of this, it is necessary to determine the location of each coating flaw and model its downstream effects to determine if the flaw needs to be mitigated before the optic is installed. For this reason, the flaw identification and characterization station (FICS) was developed for the NIF laser. FICS consists of a full-aperture imaging system which determines precise coordinates of coating flaws, a diffractive interferometer which measures the profile of a coating flaw, and a computer code which simulates the propagation of light through a flaw and predicts downstream intensification and damage.

A) Full Aperture Diffuse Light Box Imaging System

Historically, coating flaws were identified by scanning an optic with a hand held diffuse light box and visually looking for a change in reflection on the surface of the optic. Locations were estimated and marked on a hand-drawn map. To simplify and standardize the mapping of coating flaws on optics, a full-aperture diffuse light box (FADLiB) was developed for NIF optics. The FADLiB system consists of a light box twice the size of a standard final optic with a hole in the center where a high resolution camera takes an image of the optic.[2] A series of image filters and a computer code targets possible coating flaws and plots a table of coordinates for each hit.[3] In general, there are anywhere between 10-50 features on a standard 42cm x 42cm KDP or DKDP optic that are found with the FADLiB system.

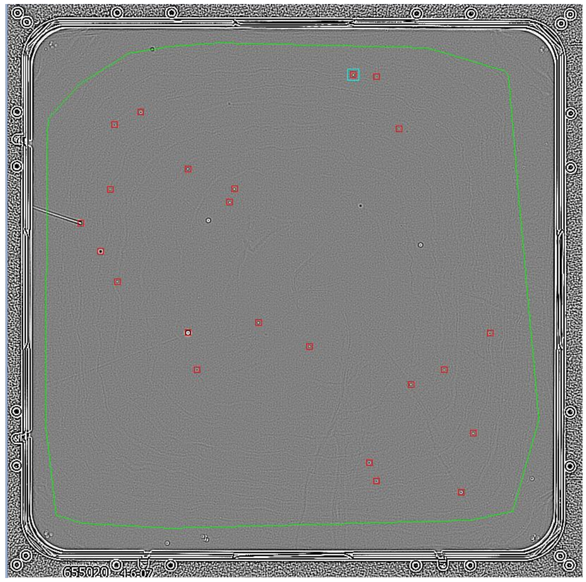

Figure 2. FADLiB image of a 42x42cm optic with red boxes around possible coating flaws.

B) Phase Shift Diffraction Interferometer

Although FADLiB can detect coating flaws, it cannot determine their detailed shape or profile. A phase shift diffraction interferometer (PSDI) is therefore used to measure the amplitude and phase profiles of each feature targeted by FADLiB.[4] The PSDI system produces phase and intensity images of each flaw with a 6 micron pixel resolution as shown in Figure 3. The phase and intensity information are necessary inputs for codes used to predict how light propagates through the defect.

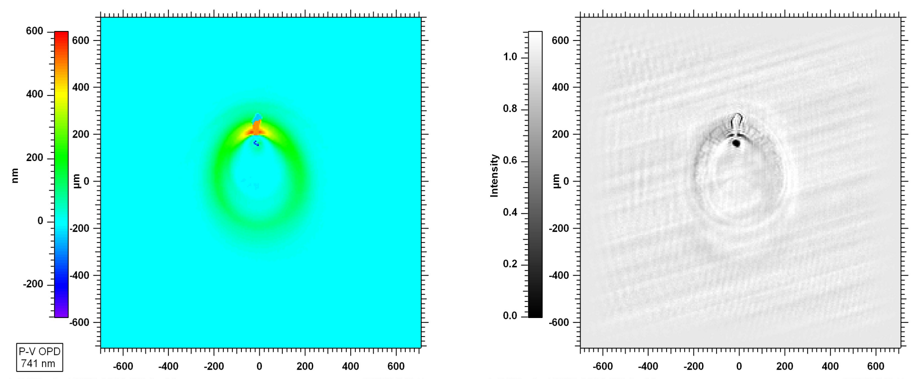

Figure 3. PSDI generated images of the phase and intensity of a typical coating flaw.

C) Final Optics Assembly Qualification (FOAQual) Code

Each flaw measured with PSDI is analyzed with a Fast Fourier Transform (FFT)-based propagation code (FOAQual) to determine whether the flaw needs to be mitigated before the optic is acceptable. The code combines the flaw phase and amplitude information generated from PSDI with a patch model for the NIF laser pulse and propagates the resulting complex electric field through the downstream final optics, taking into account diffraction, frequency conversion, and linear and nonlinear refraction. FOAQual records the fluence distribution through each optic and predicts damage using a set of damage rules based on experimental behavior of fused silica, KDP and DKDP. The probability of damage for a specific flaw is given by the damage initiation integral, $\langle N \rangle = \iint \rho(\varphi)dxdy$, where ρ is the damage density and ϕ is the fluence, and the integration is over the extent of the patch. Usually, a flaw requires mitigation if $\langle N \rangle \geq 0.03$ or the peak irradiance is greater than 12 GW/cm^2. Predicted intensification and the damage rules in the FOAQual code have been confirmed with full power shots on the NIF laser.[5]

3. HMDS SOL COATING FLAW REMOVAL TOOL

Coating flaws with the potential to cause downstream damage can originate on the PR, the SHG or the THG. Initially, steps were taken to reduce the number of controllable coating flaw precursors by improving cleanliness of the coating process. However, even after this effort was made, there were still a large number of digs and KDP particles on the optics that were uncontrollable. Typically, a KDP optic has anywhere from 10-50 coating flaws identified by FICS, and anywhere between 0-10 of these flaws typically fail the FOAQual code. A flaw removal tool (FLRT) was developed to remove the failing coating flaws from KDP optics.

The purpose of FLRT is not to remove the precursor to the coating flaw, but to remove the halo of thick HMDS sol that forms around the coating flaw. It is this halo that causes coating flaws to modulate and damage downstream optics. In the rare instance where the precursor to the coating flaw is causing damage, FLRT will not necessarily work to prevent damage. The halo around coating flaws is typically 0.5-1mm in diameter and has a thickness change of up to 1000nm. Typically, the larger the thickness change of the halo around the flaw or the larger the diameter of the flaw, the higher the likelihood there is of damage.

FLRT was created as a solvent-based mitigation tool. Because of the HMDS functional group on the sol, the coating is fully redispersible in decane. Figure 4 shows a diagram of the FLRT tool. The tool itself is made from a syringe full of decane connected to a syringe pump. Attached to the syringe is a 700µm outer diameter needle. Around this needle is a head built out of Teflon with a 1000µm bore centered on the needle. The bore in the Teflon is connected to a vacuum pump. The entire FLRT tool sits on an automated XYZ stage to allow centering of the FLRT tool on a flaw and to precisely position the FLRT tool near the surface of the optic. To mitigate a flaw, the head is centered over the defect approximately 250µm from the surface. The syringe pump dispenses approximately 300 nL of decane which dissolves away a site approximately 1mm in diameter. The vacuum pump is turned on to remove the dissolved sol and decane. The resulting site is a 1mm in diameter sol free circle on the optic. Even though this site does modulate downstream, the reduction in the maximum thickness change of the flaw reduces the intensification to a level that has a low probability of causing damage.

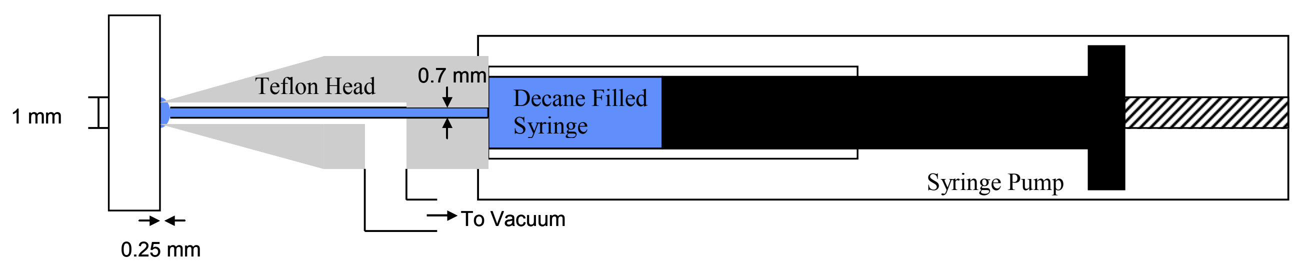

Figure 4. Schematic of the HMDS coating Flaw Removal Tool (FLRT)

Because of the high value of the optics being mitigated, a sophisticated control system is necessary to minimize human error and reduce the probability of causing physical damage to the optic. The most important device for FLRT is a noncontact displacement meter. Because the optics that are being mitigated are made of crystalline KDP and DKDP, the optics are brittle and even contact by a 0.1N LVDT leaves a permanent scuff on the optic. For this reason, a confocal positioner was used to measure the distance between the tip of the mitigation head and the optic. A confocal rangefinder takes polychromatic white light and disperses it into monochromatic light where frequencies have a specific focal point. The frequency of light which is reflected from the surface represents a specific displacement. The Micro-Epsilon optoNCDT 2401 was used for FLRT and has a 24mm working range.[6] Aside from being a noncontact device, the pros of the confocal rangefinder are that it is accurate, repeatable, and not affected by small variations in the angle of the measurement. The cons of it are that the working range of the device is limited by the antireflective coatings on the optic and the reflection of the back surface of the optic can cause a false reading of where the surface is located.

To add another layer of protection for the optic, a physical contact e-stop was developed to stop the stage from crashing into the optic if a false displacement measurement were to occur. The e-stop was built from a feather-touch (0.1N) LVDT with a Teflon head. The head of the e-stop protrudes 125µm past the tip of the FLRT tool. If any motion in the LVDT were to occur, the power to the stage is cut and brakes are applied to the stage. The momentum of the stage causes it to drift an extra 50µm before coming to a stop, which is 50-75µm before the FLRT head would crash into the optic. Although the LVDT leaves a scuff on the KDP optic, FOAQual results have shown that the spot that is left behind will not cause damage when exposed to the laser.[7] An event that causes the e-stop to engage is rare and therefore the minimal damage that is causes to the optic is acceptable.

The entire system is controlled and automated with a sophisticated LabView interface shown in figure 5. This interface automatically profiles the optic and searches for flaws based on coordinates of flaws attained from the FADLiB system. The program has several safeguards built in that determine whether the confocal device is functioning properly and whether the data collected by the probe seems believable. If the program detects any problem, it will prevent the operator from mitigating the flaw. Once a flaw is located, the user sends a command to mitigate the flaw and the computer automatically takes over. The only control that the operator has after this point is to abort the process if he feels something is wrong and to turn on the vacuum early if he feels the mitigation site is growing too large.

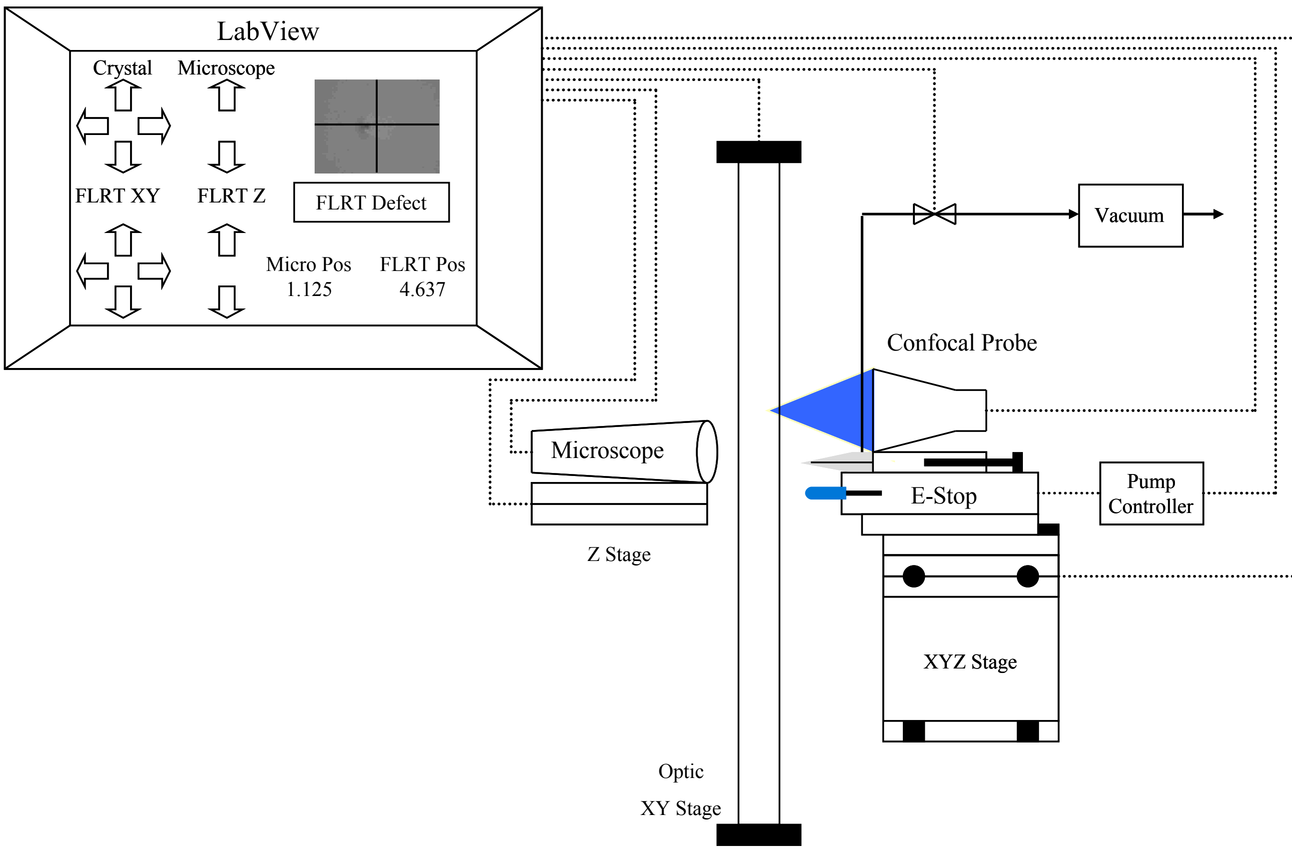

Figure 5. Schematic of the automated HMDS coating flaw removal tool system

Even after the halo is removed, there is no guarantee that the site created will pass. Figure 6 shows the before and after images of a passing FLRT site from PSDI and the resulting intensification from 351nm light. Three issues could occur that cause the mitigated site to fail after FLRT. If the site had a bad precursor left behind after FLRT, it is possible that the site itself would damage when exposed to the NIF laser or cause downstream damage. If this is the case, the optic either has to be refinished or the site has to be mitigated by some other means. The site also tends to fail if the diameter of the mitigation site gets too large. Typically, a diameter less than 1.2mm passes; anything larger than 1.2mm will pass or fail based on location of the flaw and the thickness of the coating. To prevent this, the FLRT site is controlled by the operator to a maximum diameter or approximately 1mm. Finally, a large edge on the FLRT site can cause the site to fail. After solution is dispensed and the coating dissolved away, the vacuum removes a majority of the solution. However, the vacuum still leaves a small portion of the solution on the surface of the optic. The motion of air with the vacuum can cause this to dry on the edge of the site leaving a high rim. Typically any high rim will fail through FOAQual. This failure has been resolved by mitigating the same site multiple times to remove any residual sol that may accumulate on the edge of the site.

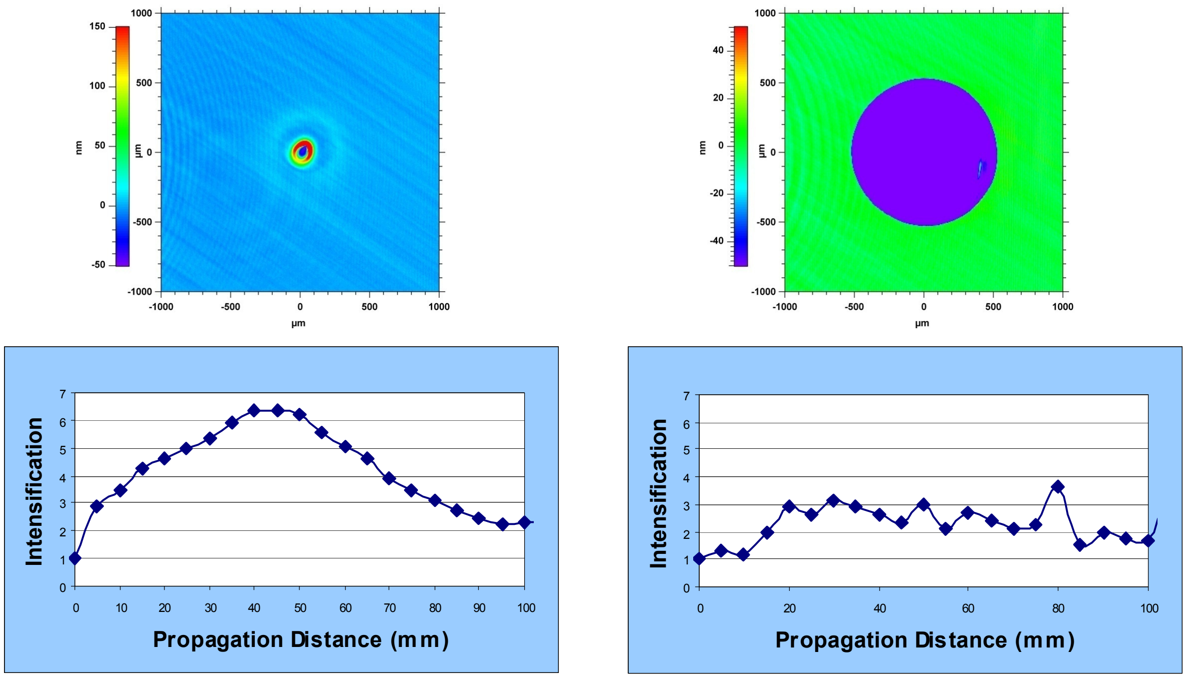

Figure 6. Before and after images of a flaw mitigated with the FLRT tool. The graphs below show the reduction in intensification that resulted after FLRT was preformed.

4. THE RESULTS OF FLRT

As of September 2008, over 300 optics have been processed using FLRT. From start to finish, it takes approximately 4 hours to run a 42x42cm KDP optic through FICS, FLRT and then back through FICS. Approximately 1220 flaws required FLRT due to failing when run through the FOAQual code. Of those 1220 sites, 1216 passed FOAQual after being mitigated (99.7% success rate). All of the sites that did not pass failed due to bad precursors and not the actual FLRT site. Several of the optics that have been mitigated using FLRT and subsequently passed FOAQual have been installed on the NIF laser and fired at full power, and there has not been any evidence of downstream modulation and damage from any sites identified by FICS or mitigated using FLRT.

5. CONCLUSIONS

The coating flaw removal tool is useful for any high energy, high intensity laser system. The tool is a decane based system that effectively dissolves away halo shaped coating flaws in HMDS sol coating by redispersing the coating solids in a small liquid drop and evacuating the resulting suspension from the surface. The resulting uncoated surface spot has a reduced intensification relative to the original coating flaw thus reducing the probability of downstream optic damage. FLRT has successfully repaired 99.7% of flaws identified on NIF optics. Although this system was specifically developed for KDP and DKDP optics on the National Ignition Facility, the concept can be adapted to any laser system. The head of the FLRT mitigation tool can be modified to mitigate different sized coating flaws and the solvent can be changed out to dissolve away different types of coating. The use of a buffered hydrofluoric acid based FLRT tool to remove hardened sol coating flaws and to mitigate defects in fused silica is a future consideration that has potentially wide-ranging applications for high energy, high intensity lasers as well.

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REFERENCES

1. E. I. Moses, J. H. Campbell, C. J. Stolz, and C. R. Wuest, "The National Ignition Facility: the world's largest optics and laser system," in *Optical Engineering at the Lawrence Livermore National Laboratory*, T. T. Saito and M. A. Lane, eds., Proc. SPIE 5001, 1-15 (2003).
2. M. Nostrand, "How we FICS NIF Optics," LMOT seminar presentation (April 26, 2007).
3. Kegelmeyer LM, Fong P, Glenn SM, , Liebman J. "Local Area Signal-to-Noise Ratio (LASNR) algorithm for Image Segmentation", SPIE: Applications of Digital Image Processing XXX (OP312, 6696-85). San Diego. (August 2007).
4. M. Johnson, "Phase-Shifting Diffraction Interferometer (PSDI)," LMOT seminar presentation, NIF-0113887 (August, 2006).
5. M. Nostrand, C. Widmayer, M. Johnson, K. Manes, "Prop-based flaw specifications for FOA optics using the damage initiation integral and a bulk intensification limit," LMOT internal Memorandum, NIF-ECMS-5017527 AA (June 20, 2007).
6. "opto 2401: Confocal chromatic displacement sensors," www.micro-epsilon.com, Y9761149-F010078MLO.
7. M. Monticelli, "Automatic flaw removal tool (AutoFLRT)," LMOT seminar presentation, (April 15, 2008).