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Status of NIF mirror technologies for completion of the NIF facility

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Invited paper

Status of NIF mirror technologies for completion of the NIF facility

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ABSTRACT

The 1600 mirrors required for the National Ignition Facility (NIF) are now coated with the last optics currently being installed. The combined surface area of the NIF mirrors is almost 450 square meters, roughly 3.4 times greater than the surface area of the two Keck primary mirrors. Additionally, the power handling specification of NIF mirrors is 19 orders of magnitude greater than that of the Keck mirrors. The NIF laser will be at least 40× greater energy than the previous LLNL fusion laser called NOVA. To manufacture these mirrors, a number of new technologies (electrolytic in-situ dressing, ion figuring, source stabilization) were used that were not available for previous fusion laser optics. Post deposition technologies designed to increase laser resistance (off-line laser conditioning, solarization, air knives) have also been utilized. This paper summarizes the differences in technologies used to manufacture NIF mirrors from those used for previous fusion lasers and examines potential future technologies that would enable higher fluence operations and extend lifetimes.

Keywords: laser resistance, contamination, solarization, optical finishing, multilayer coatings, mirrors

1. INTRODUCTION

The National Ignition Facility (NIF)[1-5] is a stadium-sized 192 beam laser constructed to create fusion conditions in a controlled laboratory setting. In order to achieve these extreme conditions, 1600 high fluence mirrors and polarizers are needed for beam steering. The NIF laser is the culmination of almost 40 years of laser and optics technology development at Lawrence Livermore National Laboratory, Universities, Institutions, and Private Industry. Through those four decades, optical fabrication and coating technologies have changed significantly. In order to achieve a 3-5 increase in finishing and coating production for NIF while achieving aggressive cost targets, a development and facilitization effort occurred in the 1990's.[6-7] This was followed by a nine year production phase commencing in 2000. The focus of the development program was on improving the determinism of the optical manufacturing process, reducing hand-working operations, and improving laser resistance. Future development activities for NIF mirrors will focus on increasing laser resistance to enhance the performance capabilities on NIF beyond the initial design goals and to reduce the NIF operational costs.

2. MIRROR AND POLARIZER FINISHING TECHNOLOGIES

One of the most labor intensive steps in mirror fabrication prior to NIF was the loose-abrasive grinding process. Fixed abrasive grinding processes are less labor intensive, but have poor figure control. The grinding wheel fills with swarf (glass grinding byproducts) and dulls quickly. Redressing the wheel to eliminate the swarf and expose fresh diamonds leads to poorly controlled mirror surface figures. Unfortunately figure correction during polish out has a much slower removal rate than the grinding processes. The solution to this problem was scaling Electrolytic In-Situ Dressing (ELID) to meter-sized surfaces.[8] ELID is a process where a current across a fixed abrasive wheel acts as a catalyst to cause a controlled corrosion of the wheel matrix that holds the imbedded diamonds used to fine grind the mirror substrate surface as illustrated in figure 1. A controlled corrosion prevents the buildup of swarf and exposes fresh diamonds eliminating the need for manually redressing the grinding wheel resulting in a low microroughness surface with a controlled surface figure requiring significantly less polish out.

In order to decrease polishing removal times, a synthetic lap polishing process was adopted for NIF optics because of higher removal rate. To achieve final figure, a more traditional pitch ring polishing machine was used. However, the 144" diameter pitch ring polisher contains multiple control points that are computer controlled and significant steps were taken to stabilize the environment around the polishing machines. An example of the lap flatness with computer control is illustrated in figure 2.[9] Through the use of these technologies, the number of polishing and testing iterations were reduced typically 5-10×.

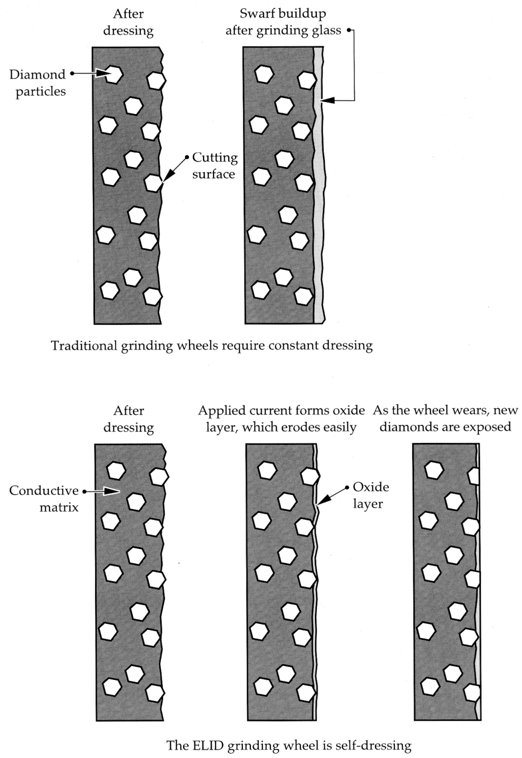

Figure 1. A comparison of traditional and ELID grinding

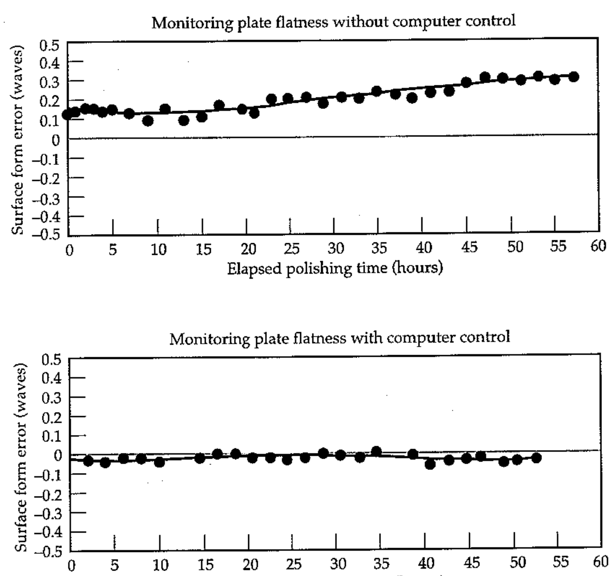

Figure 2. Without computer control or highly skilled operator intervention, the surface developed by a polishing lap diverges from flatness.

Very high homogeneity BK7 was cost prohibitive for the 9 cm thick NIF polarizers. To overcome the inherent transmitted wavefront errors, the second surface of NIF polarizers were ion figured with the same technology used on the Keck mirror segments. Ion figuring is a highly deterministic small-tool computer controlled figuring process. Post ion figuring correction was quite impressive as illustrated in figure 3, with improvement factors typically around 4-5× for the

P-V and RMS gradient. Smaller improvements were seen in the PSD and in some cases very minor degradation occurred. The great majority of polarizers only required a single ion figuring iteration.

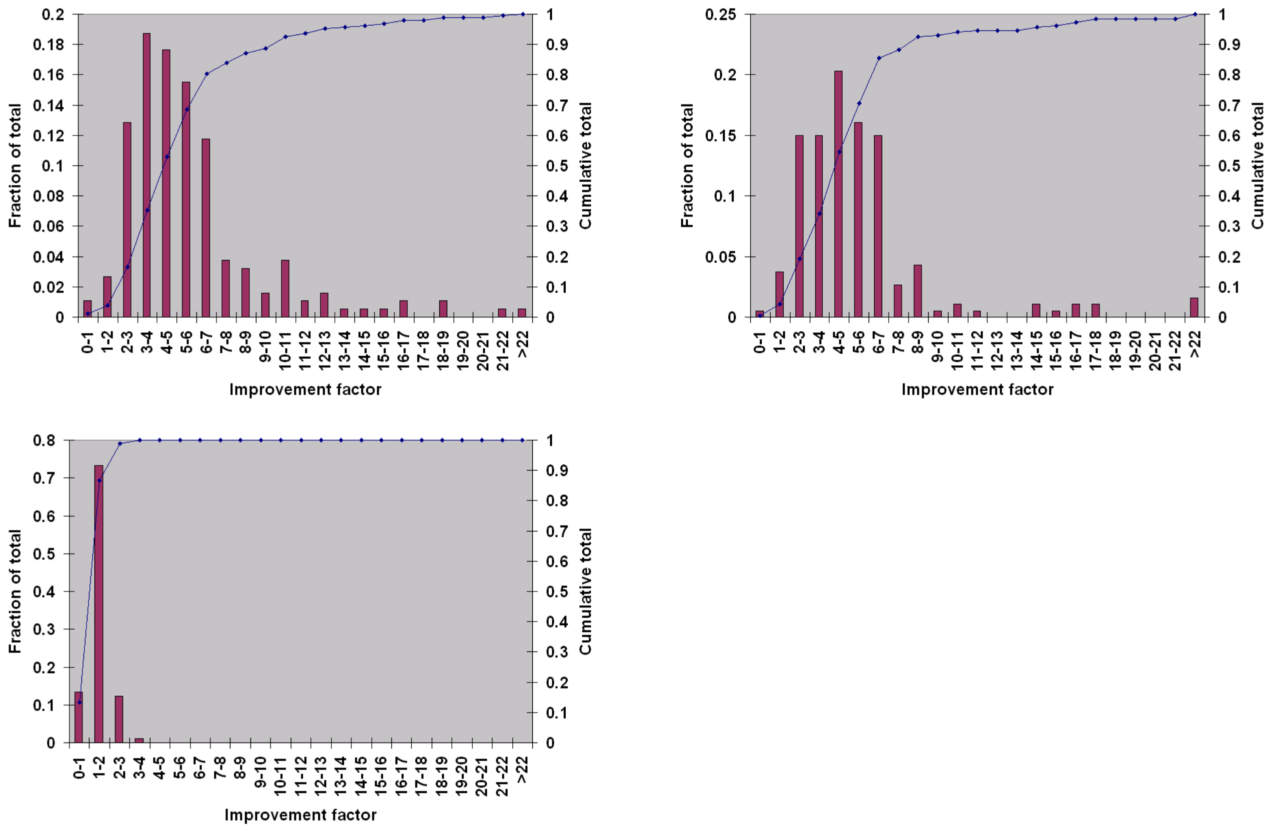

Figure 3. Transmitted wavefront improvements due to ion figuring image P-V (top left image), RMS gradient (top right image), and PSD (bottom image).

3. OPTICAL COATING

The 10 beam NOVA laser preceded the NIF laser at LLNL. The mirrors were round unlike the rectangular NIF mirrors with improved beam packing density. Nova mirrors were up to a meter in diameter to reduce the laser fluence and the original mirrors were manufactured using electron beam deposition with what is considered now a low laser resistant material combination (TiO_2 & SiO_2). Eventually higher fluence material combinations such as ZrO_2 or HfO_2 & SiO_2 were used. Later on NOVA mirrors were systematically exposed to a fluence ramp from a low to high energy to laser condition the mirror causing a ~2× increase in the laser resistance of the mirror via on-line laser conditioning.

Unfortunately the more laser resistant material combinations have a smaller ratio of refractive index leading to narrow bandwidth. This is particularly problematic for Brewster's angle plate polarizers. To improve the polarizer manufacturing yield by 3×, a number of changes were incorporated to the deposition process. Firstly, the starting material was changed to hafnium metal leading to a significantly more stable deposition plume. A nearly stable e-beam over a molten metallic source is significantly more stable than an irregular oxide surface swept by an e-beam as illustrated in figure 4. Multiple crystal monitors were installed in the coating chamber to monitor the deposition plume and hence optimize the sweep parameters. In addition to the improved stability, the hafnium metal coatings have significantly fewer coating defects, less laser-induced surface modifications, and improved quality of the film interfaces.[10]

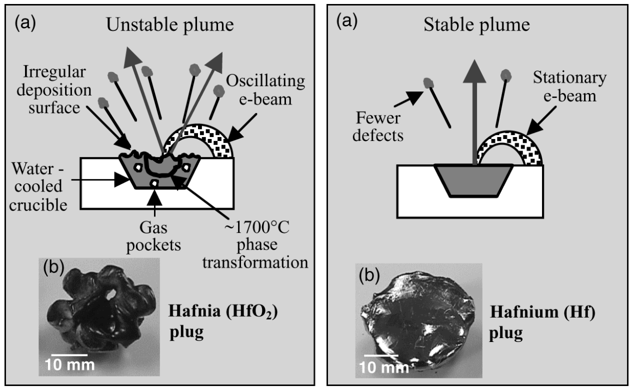

Figure 4. (a) coating source stabilization
(b) starting material plugs

Raster-scan laser conditioning stations (figure 5) were built to condition the entire mirror aperture as well as provide a quality assurance tool to verify the mirrors meet the laser resistance requirement prior to installation.[11-12] These conditioning stations have a scatter based diagnostic to track surface changes for post fluence stability testing. A plasma detector is also part of the diagnostic package. Plasmas generally occur when coating defects are ejected and can lead to a plasma scald or micro-roughening of the surface. Although this damage morphology is quite stable, unfortunately the contrast of an incident beam is increased leading to a greater risk of laser damage to downstream optics.[13] Mirrors with plasma scald fractions greater than 3% are not used on NIF.

Figure 5. Off-line laser conditioning station.

Finally phase-measuring interferometers were wavelength converted to the primary operational wavelength of the mirrors (1053 nm) to eliminate false reflected wavefront errors due to out of band reflections.[14] Specifications were written that allowed a modest amount of power to be removed from the plano reflected wavefront measurements thus utilizing deformable mirror[15] correction and/or lens translations to achieve laser collimation. The interferometer cavities also have the ability to control relative humidity since the mirrors operate in the NIF cavity (relative humidity <2%) and and switchyard / target bay with a relative humidity of 40 +/- 6.5%. The argon used in the high fluence transport area is intentionally humidified because e-beam coatings tend to have a smaller wavefront change at higher relative humidities thus making it easier to tune the coating stress of the transport mirrors to minimal curvature. This also facilitated alignment in ambient conditions (lab air) before switching over to high fluence operation in Argon.

4. CONTAMINATION CONTROL

Mirror coatings were tested for laser resistance in the presence of contamination. Contaminates of different sizes consisting of metals, oxides, and organics were used. The results clearly illustrate that contamination can reduce the laser resistance of mirror coatings.[16] In laser operations, the mirror cleanliness depends on the cleanliness of the environment and the orientation of the mirror. Gravity tends to keep mirrors that face down significantly cleaner than mirrors that face up. In open architecture laser systems such as the Omega laser at the Laboratory for Laser Energetics at the University of Rochester, the mirrors are cleaned in place. The NIF laser, however, is sealed negating manual cleaning of optical components.

A gas knife concept illustrated in figure 6 is being implemented on NIF to overcome the inability to easily manually clean the upward facing mirrors.[17] A laminar burst of gas at a grazing incident angle flows from a slit in a tube that runs parallel to each mirror edge, blowing across the mirror surface to dislodge particular contaminates. As expected, the larger the particle size and the closer the particle is to the gas knife, the greater efficiency of their removal as illustrated in figure 7. A in-situ damage inspection station (Final Optics Damage Inspection or FODI) has been built into NIF.[18] This system can also be used to look at the high fluence NIF transport mirrors to detect and track any laser-initiated surface modifications or contamination-induced damage.

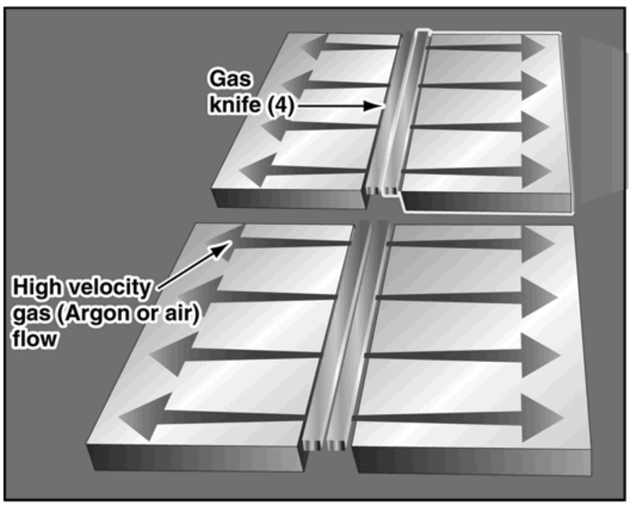

Figure 6. NIF transplant mirror gas knife to remove particles.

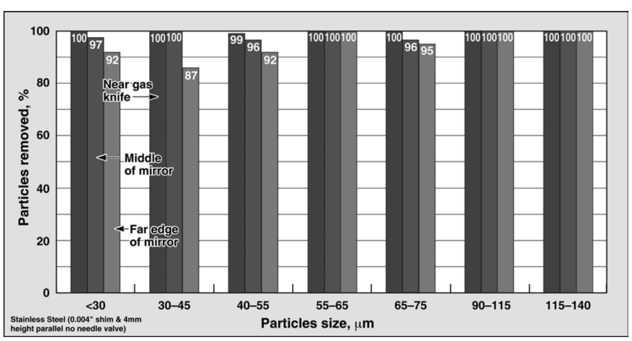

Figure 7. Gas knife particle removal efficiency.

5. BACKSCATTER CONTROL

Light that backscatters from the plasma surrounding the target must be suppressed to prevent damage to upstream NIF optics. The backscatter is caused by stimulated brillion scattering (~351 nm) and stimulated raman scattering (400-700 nm). To suppress the transport of these wavelengths up the NIF beamline, the transport coatings were designed to have low reflectivity in these wavelength bands. High reflectivity is needed at the primary NIF wavelength transported by the mirrors (1053 nm) and a 374 nm pilot wavelength is used for alignment through the frequency tripled area of the NIF laser just before the beam enters the target chamber. Mirrors in the main cavity (laser bays) only have high reflectivity requirements at the 1053 nm wavelength since target backscatter does not propagate that far into the laser facility. Each of the NIF beams has 4-5 transport mirrors so a specification of R<33% used in the backscatter wavelengths leads to a transport reduction of 2 orders of magnitude. A goal of R<3% leads to a transport reduction exceeding 6 orders of magnitude. An example of the NIF transport mirror spectral performance is illustrated in figure 8.

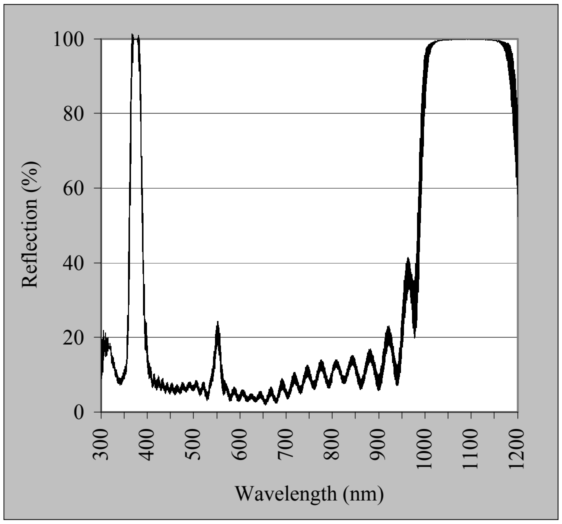

Figure 8. Averaged spectral characteristics of 22 NIF transport mirror coating runs. The line width at each wavelength is equal to the standard deviation.

The mounting features for NIF transport mirrors consist of three expansion mandrels that mate into holes cored into the back of the mirrors. The high transmission coatings at the SBS & SRS wavelengths strike the metallic expansion mandrels at up to 2 J/cm2 (~3 ns), at least ten times greater than the damage threshold of metal. To absorb this laser light before it strikes the mounting hardware, the mirrors are exposed to a Cobolt 60 gamma source which visibly darkens the BK7 material through the creation of color centers (figure 9).[19] Laser resistance and reflected wavefront tests have validated that performance of the mirror is unchanged due to the solarization process. Over time the transport mirrors will tend to bleach thus increasing the SBS and SRS transmission. Bleaching rate tests were performed at various elevated temperatures to determine the bleaching rate at ambient conditions. The results are in figure 10.

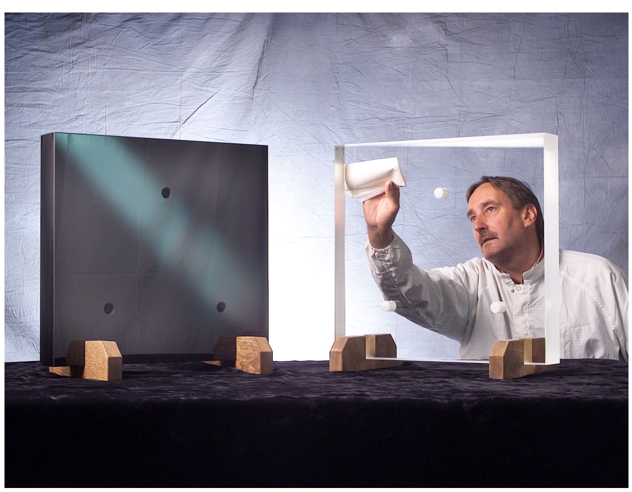

Figure 9. NIF transport mirrors after gamma irradiation (left side) and before gamma irradiation (right side)

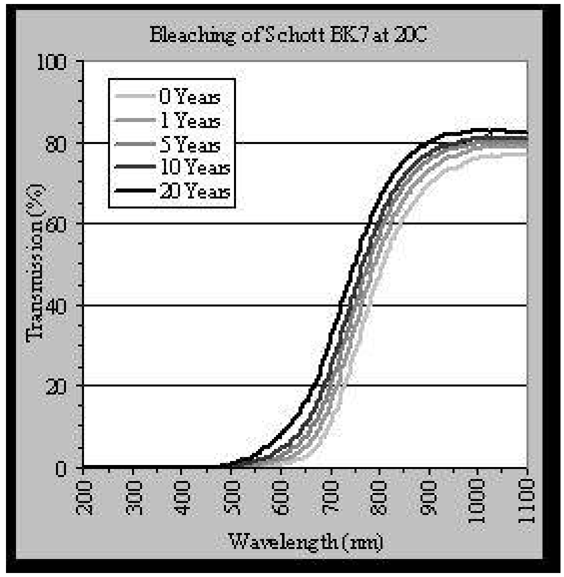

Figure 10. Bleaching rate of gamma irradiation BK7

6. DAMAGE GROWTH CONTROL – FUTURE DEVELOPMENT

A significant amount of research has gone into developing techniques to arrest laser damage growth to extend fused silica and DKDP optic lifetimes.[20-23] The concepts that have been developed are locally melting damaged fused silica surfaces with CO_2 lasers or micro-machining DKDP surfaces with a high speed diamond single crystal tool. Unfortunately optical coatings consist of multiple materials with different expansion coefficients making local heating problematic. Micro-machining thin films is also difficult. A number of coating mitigation strategies[24] illustrated in figure 11 have been attempted although clearly more development work is needed before a process could be utilized for NIF operations.

Long pulse or CW laser based mitigation techniques have been largely unsuccessful. Crazing occurred with CO_2 mitigation and excimer mitigation often left residual coating material in the mitigation area that was susceptible to damage. The only laser based system that has shown any significant promise is a short pulse burst approach, however, the spot sizes are too small and robust industrial short pulse lasers are not yet available. Mechanical approaches such as Magnetorheological Finishing (MRF) and the single-crystal diamond tool have also been explored, but not developed. In order to achieve a modestly deep pit (~5 microns), MRF spots have a fairly large area where coatings are partially removed. After laser exposure, the hafnia layers demonstrate significant change possibly the result of higher electric fields through the wedged layer or iron contamination from the polishing slurry. Additionally the single layer hafnia layers have significantly lower laser resistance than silica layers so exposure of the hafnia layers may be problematic. Two micro-machining approaches were attempted using a raster scan and a spiral pattern. The spiral pattern tended to have much less edge fractures in the coating, however, the laser resistance is only marginally better than the growth threshold of catastrophic coating damage. Certainly this is a growth area for coating damage research.

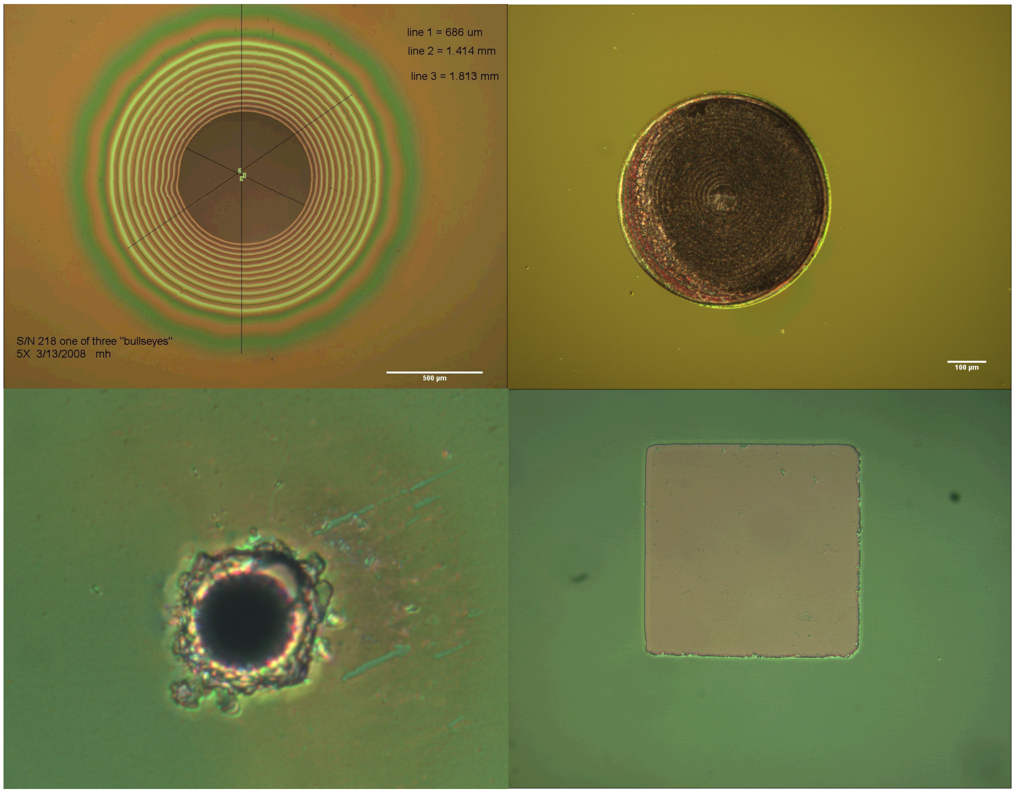

Figure 11. Coating mitigation sites created by MRF, single crystal diamond high speed machining, and short pulse “burst mode”, and excimer laser (top left to bottom right). The mitigation features range in sizes from ~50 microns to >1 mm.

7. CONCLUSIONS

The NIF mirrors have utilized advanced finishing, coating, contamination control, backscatter mitigation, and laser conditioning processes to safely propagate the high energy levels expected in the NIF laser facility. These new technologies are enabling a step forward in manufacturing mirrors with greater laser resistance and hence higher operational fluences than any prior fusion laser. Further increases in mirror laser resistance are likely to occur from continued defect reduction or post mitigation strategies to arrest damage growth sites.

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