LONG-TERM SURVIVAL OF GRAZING-INCIDENCE METAL MIRRORS FOR LASER FUSION

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The grazing incidence metal mirror is a promising option for the final optic in a laser-driven inertial fusion energy power plant. It has been pursued as an alternative to multi-layer dielectric mirrors based on expectations of higher radiation damage resistance. Aluminum offers high reflectivity over a broad range of wavelengths extending deep into the ultraviolet part of the spectrum, and thus offers special advantages for an excimer laser driver. In this article, we describe the fundamental phenomena of laser-induced metal mirror damage and lifetime, strategies for mirror fabrication, our experimental facility and techniques, and the results of fabrication and test campaigns over the past several years.

I. INTRODUCTION

The final optic in a laser-IFE power plant experiences direct line-of-sight exposure to target emissions, including neutrons, x-rays, high-energy ions and debris. It must withstand this environment reliably over many months of continuous operation, while simultaneously meeting stringent optical requirements. The primary purpose and minimum requirement on the final optic are to deflect the beam so that the remaining optics are protected against these threats. Other optical functions such as focusing, steering or wavefront correction can be performed upstream of the final optic.

Early in our research program we established goals for the lifetime, surface quality and exposure limits for the various threats that the optic will experience, including neutrons, ions, x-rays and the laser itself.[1] We are trying to produce reliable optics that can withstand up to 5 J/cm^2 laser fluence over 3×10^8 shots with less than 5% absorption loss and $<\lambda/2$ wavefront degradation.

There are several possible methods of displacing a laser beam, including transmissive refractive optics (such as a wedge), transmissive diffractive optics (such as a Fresnel lens) and reflective mirrors. In 1991, a "grazing incidence metal mirror" was proposed as a robust, radiation damage resistant alternative to multi-layer dielectric mirrors for the final optic of a laser IFE power plant[2]. Among the most serious issues with metal mirrors are the lifetime and resistance to damage induced by the laser driver itself. Metal mirrors absorb a significant fraction of the incident laser energy, causing long-term accumulation of cyclic thermomechanical damage. Operation at a grazing angle with properly polarized light allows the reflectivity to be increased significantly, providing much reduced absorption and increased damage resistance. In our studies, we fixed the angle of incidence at 85˚, providing approximately 10 times lower absorptivity and 10 times larger footprint as compared with the beam cross section.

In 2001, we embarked on a multi-year program of mirror development and testing under prototypical conditions. We established an excimer laser test facility at UC San Diego with prototypical wavelength, pulse length and environmental conditions. We fabricated mirrors using a variety of deposition and finishing techniques. Long-term exposures were carried out to define fatigue lifetime curves, and the underlying mechanisms of damage were explored through observations of morphology changes following exposure.

The most attractive mirrors were made using Al and Al alloys, due to the very high reflectivity of Al deep into the UV part of the spectrum. Thick coatings made by either electroplating or sputter coating, and then either diamond-turning (DT) or chemically-mechanically polishing (CMP), have provided the best results. Solid solution alloys of Al appear to offer the best combination of reflectivity, surface quality, small grain size and mechanical strength. We tested CMP-polished Al-1%Cu and characterized damage resistance for shot counts exceeding 10^7.

II. LASER-INDUCED DAMAGE IN METALS

Laser-induced damage tends to occur first in an optic containing defects. These defects may occur as a result of contaminants (within the bulk or on the surface), poor adhesion of a coating, or poor surface finishing. Proper care in fabrication can eliminate or at least reduce these defects to a large degree. When all of the imperfections are removed, still a fluence limit will exist as a result of bulk microstructural limitations of the metal.

In this regime, laser-induced multi-pulse damage to metal mirrors is primarily a thermomechanical process. Thermal stress-induced degradation of metal mirrors was studied in detail by Musal[3]. An empirical model for multi-pulse damage to metal mirrors was later presented by Lee[4] *et al*, who examined the effect of spot size on damage threshold. Long-term multi-pulse laser exposure leads to microstructural evolution analogous to mechanical fatigue. Each laser pulse produces rapid heating at the mirror surface, resulting in a steep thermal gradient and inducing high thermal stress. For example, a fluence of 10 J/cm^2 will result in approximately 10 mJ/cm^2 absorbed into the mirror surface assuming 99% reflectivity and a factor of 10 spreading of the laser footprint due to the grazing angle of incidence. The mirror surface temperature rises tens of degrees with stresses approaching the yield point of aluminum:

$$\sigma \approx \frac{\alpha E \delta T}{3(1-\mu)} \tag{1}$$

where the thermal expansion coefficient $\alpha = 23\text{x}10^{-6}$ K^{-1}, the modulus of elasticity E = 69 GPa and Poisson's ratio μ=0.37 for pure Al. Depending on the laser pulse length, the thermal gradient, and therefore thermal stress will vary. The steep thermal gradient and high stresses occur within several microns of the mirror surface and are imposed over many cycles.

The morphology of damage and the fluence limit depend greatly on the microstructure of the metal. For example, we have seen evidence of various modes of plastic deformation in the microstructure, such as slip plane motion and grain rotation (see Fig. 1). In designing a robust aluminum mirror, it is important to increase resistance to plastic deformations by controlling the grain size and by strengthening the material against defect transport.

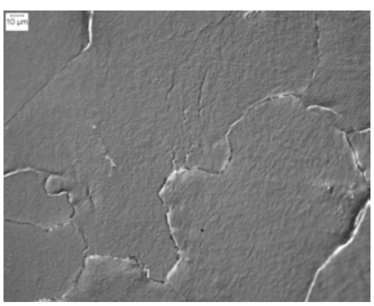

Fig. 1. Mechanisms of laser-induced damage in metal mirrors: grain boundary rotation

III. DAMAGE TEST FACILITY

The UC San Diego laser-matter interactions laboratory contains several Joule-class solid-state and gas lasers with pulse lengths in the range of 0.1-100 ns. For all of the experiments described here, we used KrF excimer lasers operating at 248 nm with 10-50 Hz repetition rate and energy in the range of 200-400 mJ. The footprint of the beam on target is an elongated trapezoid with area of the order of several mm^2, which is much larger than the characteristic thermal, stress and damage scale lengths. A slight increase in fluence occurs along the beam propagation direction due to the final focus lens, but this variation is measured and maintained small by proper optical design. Experiments are performed in a cryo-pumped vacuum chamber in order to minimize chemical interactions, which can occur at excimer wavelengths. Figure 2 shows a schematic of the test arrangement.

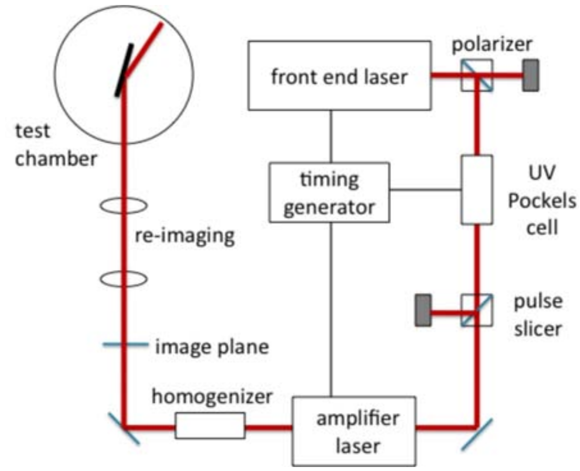

Fig. 2. Test facility arrangement

We have the capability to operate in an oscillator-amplifier configuration, in which a seed pulse is temporally sliced using a heavily deuterated KD*P Pockels cell that retains transmission at 248 nm, and then single-pass amplified to obtain adequate energy for testing. Figure 3 shows an example of the temporal profile at 248 nm both with and without pulse slicing.

In addition, we utilize a custom-made imaging homogenizer consisting of two microlens arrays and a Fourier lens. The homogenizer uses a long working distance from the final imaging optic to the test article in order to avoid damage to the vacuum chamber entrance window and to reduce the intensity variation along the test area. Figure 4 shows the spatial intensity distribution at the test mirror location using the homogenizer.

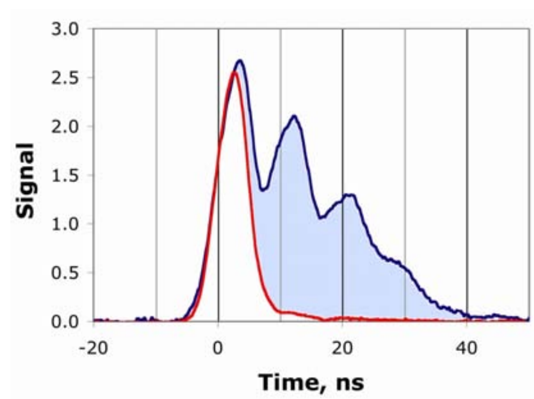

Fig. 3. Temporal pulse shape with and without slicing

Variations of the order of 5% remain, but those variations have long scale length and are independent of laser operating condition. Without the homogenizer, localized peaks occur, and those peaks vary from shot to shot and as a function of the fill gas age, repetition rate and other laser parameters. Note, pulse slicing and homogenization were not used in every experiment, as these capabilities were added incrementally during the research program.

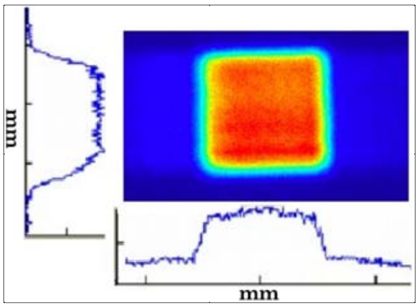

Fig. 4. Homogenized beam profile

At a grazing angle of incidence with 248-nm light, defects larger than about 50 nm begin to absorb energy at a greater rate than the surrounding smooth surface. This leads to "unstable" growth of damage and ultimately to catastrophic local failure. This places a limit on the initial size of defects, and also complicates data acquisition. In order to avoid melting induced by the unstable growth of a defect, a rapid laser shutdown system was needed. We developed a high-speed vision system that images scattered light under the footprint of the main laser that results from both the laser itself and a HeNe probe laser. The main laser is allowed to fire only when the vision system indicates the amount of scattered light is below an empirically established threshold. Figure 5 shows an example image acquired prior to shutdown caused by unstable growth of a damage site near the center.

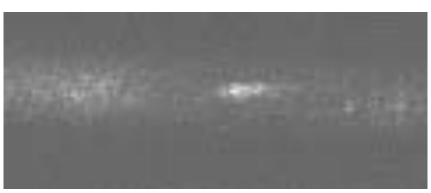

Fig. 5. Vision system image prior to automated shutdown. A HeNe laser backlighter is used to enhance the signal.

IV. OPTIC FABRICATION TECHNIQUES

The method of fabrication determines both the quality and the damage resistance of metal mirrors. We experimented with numerous fabrication techniques, including polishing of thick Al and Al-alloy blocks, thin film deposition onto various substrates, and several surface finishing techniques including single-point diamond turning and chemical-mechanical polishing.

Aluminum is a difficult material to use as a high-energy laser optic due to its low yield strength and propensity to grow large grains. Grain rotation is one of the most commonly observed mechanisms of damage in Al mirrors, such that control over grain size is a critical requirement for a successful optic.

For thin film deposited mirrors, we consistently found that coatings thinner than the thermal penetration depth of the laser heating (of the order of several microns for a 10-20 ns pulse) exhibited early failure. The mechanisms of failure included both localized detachment and defect accumulation at the optical surface. Therefore, we sought fabrication techniques capable of producing rather thick coatings, of the order of at least 5-10 µm.

IV.A. Alumiplate coatings

Alumiplate[5] is a patented process for electroplating high purity aluminum onto various conductive substrates. We chose to produce mirrors using this technique due to the ease with which large, fully-dense, thick (>100 µm) pure coatings could be fabricated. This process leaves a fairly rough surface, requiring postprocessing to produce acceptably smooth surface finish. We prepared samples by coating Al alloy substrates and then either single-point diamond turning or polishing the surface.

Figure 6 shows a micrograph of a diamond-turned test sample. Diamond turning lines are easily evident, but their height is below a few nm. Grains are also evident in the photo; their size is in the range of 10's of microns. Figures 7 and 8 show surface height profiles for diamond-turned and polished samples. Although turning lines appear prominent in microscopy images, their height is well within our specifications. CMP post-processing was found to provide very smooth surfaces as well, with rms roughness less than 2 nm.

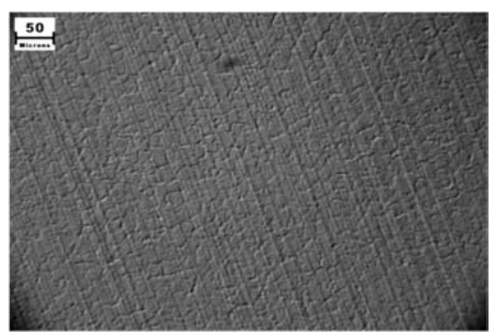

Fig. 6. Microscopy of a diamond-turned alumiplate mirror

IV.B. Sputter coatings

As an alternative to electroplating, we produced thick Al coatings by evaporative and sputter coating processes. For example, a coating >15 µm thick was produced and then diamond-turned to smooth the surface. We have observed that the grain size of evaporative and sputter coated mirrors varies substantially depending on the process parameters. The grain size with pure Al generally is **not** significantly less than that of Alumiplated samples.

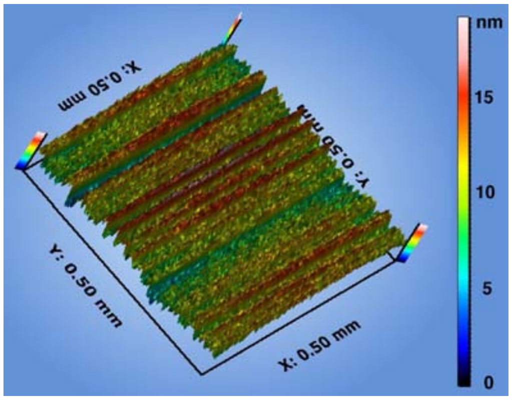

Fig. 7. 2D surface profilometry for a diamond-turned Alumiplated mirror

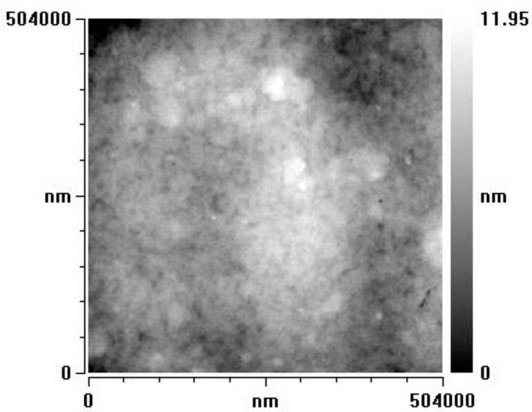

Fig. 8. Surface profilometry for a CMP polished mirror

IV.C. Alloy coatings

Alloying is a possible means to alter the basic mechanical properties of the mirror surface. Additions of only a percent or two of a second constituent can have a large effect on hardness, elastic modulus, and tensile strength.[6] In our experience, precipitates are very dangerous, as they invariably absorb incident light at a much greater rate than pure Al. If a precipitate is more than 10-20 nm in diameter, then reduced damage threshold would most likely result. Therefore, we explored solid solution alloys of Al with atom fractions low enough to avoid any risk of precipitation – in the range of 0.5-2%.

We evaluated a large array of potential alloys of aluminum to be used as a sputter target, including those containing Cu, Mn, Si, Mg and Zn. We rejected any whose strength derives from cold working, which is difficult to implement with thin film deposition. Copper was chosen as the primary solute of interest because it does not substantially reduce reflectivity, is known to reduce grain size and produce a more specular surface, and improves the yield strength with small additions as low as 0.5%.

Using a sputter coating system it is easy to control the composition of the coating by using an alloy sputter target. We fabricated Al mirrors using 0.5, 1 and 2% Cu sputter targets. Coatings as thick as 10 μm have been produced at the UCSD nano3 fabrication lab in daylong coating runs using a Denton Discovery 18 sputter coating system. The resulting coatings exhibited two remarkable properties. First, the surface remained nearly specular, even with coatings exceeding 5 microns. Second, the grain size was under 1 μm – considerably smaller than we had seen previously with pure Al coatings. The presence of Cu in the coating clearly acts to frustrate grain growth, and should significantly improve performance. Figure 9 shows an SEM image of a 10-micron thick 0.5% Cu coating prior to surface finishing. Grain size is ~1 μm, except for pyramidal crystallites that begin to grow as the film thickness reaches these high levels. Postpolishing by CMP results in rms roughness of 1–2 nm.

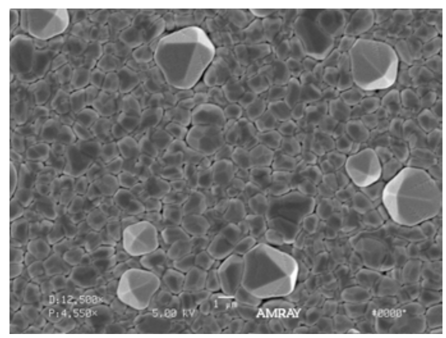

Fig. 9. SEM image of an alloy mirror prior to surface finishing

V. TEST RESULTS

Experiments were performed by fixing the laser energy, hence fluence on the surface, and then exposing samples until damage was imminent as determined by the vision system described in Section III. Samples were translated to a fresh region of the surface in order to repeat the experiment or to operate at a different fluence level. Each of these long-term exposures produces a single data point on a fluence curve.

The majority of the data were obtained using the natural 20-25 ns pulse length of the excimer laser. Section V.A. summarizes the data obtained with these "long" pulses. Due to uncertainties in the scaling with pulse length, a test campaign was performed in which the pulse length was reduced to 4-5 ns. The results of damage scaling with pulse length are presented in Section V.B.

V.A. Long-pulse results

Extensive data have been obtained using 20-25 ns pulses from our 248-nm KrF laser, for dozens of test mirrors using many different deposition and surface finishing techniques. In general, the data obey a classical "fatigue" curve in which lifetime increases according to the formula[7]:

$$\mathbf{F_n = F_1\, N^{(s\text{-}1)}} \qquad (2)$$

The parameter "s" depends on the mechanical properties of the mirror, and must be determined empirically.

This formula, consistent with all of our experience, suggests that damage to a well-fabricated metal mirror is **cumulative** and not caused by initiation effects such as commonly occur in transmissive optics such as glass. This is a **major** difference in damage evolution compared with transmissive optics: metal mirrors tend to damage gradually and predictably if no major defects exist.

Related to this, we have observed two regimes of damage as a function of the shot count. We call these "rapid onset" and "high cycle" damage.[8] Rapid onset occurs at discrete locations, leaving the majority of the surface undamaged. If the surface survives these early failures caused by localized defects, then high-cycle damage tends to follow a fatigue curve such as Eqn 2.

Figure 10 shows damage data for a range of mirror surfaces and compares them with a fatigue fitting curve using s=0.76. Alumiplated mirrors survive high fluence for low shot counts, but fail to meet our criterion of 5 J/cm^2 up to 3x10^8 shots. Damage as seen in Figure 11 occurs at numerous discrete locations corresponding with grain boundaries, where rotations cause surface roughness leading to increased absorption.

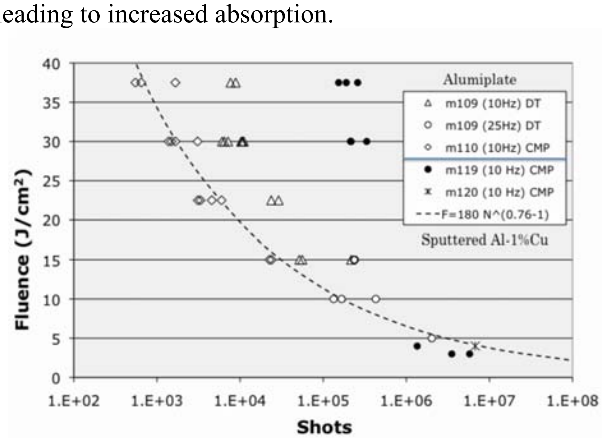

Fig. 10. Long pulse damage fluence data comparing Alumiplate and sputtered alloy mirrors.

Alloy mirrors, identified in Fig. 10 with solid circles, exhibited a factor of approximately 3 times improvement in damage resistance corresponding to the approximately 3 times higher yield strength expected. However, at high shot count above 10^6, the surfaces failed at relatively low fluence due to highly-localized (width of 10's of microns) detachment of the film. The cause of detachment was subsequently identified as a problem in wafer preparation and coating, which has been remedied. New data are currently being acquired to demonstrate the higher damage resistance of alloy coatings at high cycle.

Fig. 11. Damage to Alumiplate mirror at high cycle count.

V.B. Short-pulse results

The laser pulse length is expected to affect laser-induced damage in several ways:

1. A longer laser pulse leads to deeper penetration of the thermal diffusion wave,
2. A longer pulse will subject the surface to stress over a longer period of time, and
3. A longer pulse **at fixed pulse energy** leads to lower surface temperature and therefore lower stress.

To first order, it is common to assume that the peak temperature is the dominant consideration in determining the thermal stress and hence stress-induced damage. Using a 1-dimensional thermal diffusion approximation, the surface temperature increases as the square root of time following a step change in the heat source. In that case, the incident heat flux q" required to achieve a given temperature in the case of a longer pulse would be reduced by $t^{1/2}$, but the required **energy** would be increased by $t^{1/2}$ (since the total energy scales as q"t).

Due to the complexity of pulse length scaling, we measured the effect on laser-induced damage experimentally.[9] We first collected damage fluence data using a "long" 25-ns on a diamond-turned alumiplated test specimen with 3 nm rms roughness and maximum peak-to-valley of 20 nm. The short pulse damage fluence was predicted using a 1-D thermal diffusion model and assuming the peak surface temperature dominates the behavior. Finally, we produced an IFE prototypic "short" laser pulse (~5 ns) and exposed fresh locations on the **same** mirror specimen to collect short pulse damage fluence data for comparison.

Figure 12 plots the results. The long-pulse data have higher damage fluence than the short-pulse data. Scaling the data by $t^{1/2}$ results in the lower curve. The actual short-pulse results are higher than this prediction – much closer to the long-pulse results. This is undoubtedly due to the effects listed above: shallower penetration of the stress field and shorter time of exposure for the short pulse.

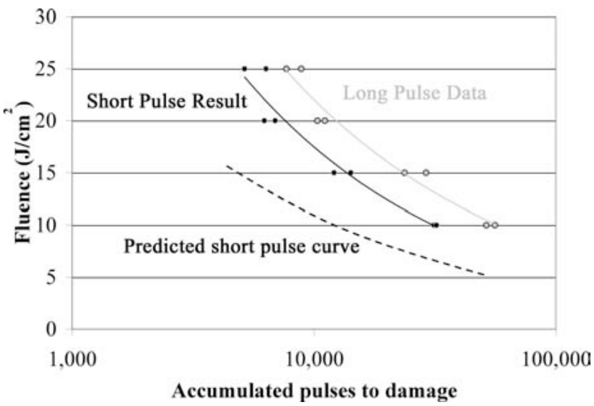

Fig. 12. Short pulse damage fluence data compared with prediction based on thermal diffusion

VI. CONCLUSIONS

A wide range of aluminum-based mirrors have been fabricated and subjected to high-cycle high-fluence laser irradiation. If the optical coating is sufficiently thick to prevent interfacial stress-induced damage, then damage to high-quality defect-free mirrors occurs as a result of long-term thermomechanically induced microstructure evolution. This evolution is characterized primarily by defect transport and grain boundary rotation. For defect-free surfaces with rms roughness below a few nm, the damage resistance depends primarily on the size of grains and yield strength of the alloy.

Several conclusions have become clear as a result of numerous damage study experiments:

1. The most common mechanism observed in high-cycle damage involves grain rotation in polycrystalline Al and Al alloys. Smaller grains provide higher yield strength, and also tend to restrict the motion of grains.
2. Optical coatings thinner than the thermal penetration depth create large interfacial stresses on substrates with different expansion coefficients than Al. The thermal penetration depth for pulses of the order of 10-20 ns is several microns, requiring rather thick coatings compared with conventional optics.
3. Even in cases where a thin Al coating was applied to an Al alloy substrate, early failure was observed. In this case, defects at the interface experience a relatively high strain field due to laser heating and tended to propagate to the surface.
4. Purity of the base material and the surface are both extremely important for damage resistance. Precipitates in the alloy invariably lead to increased absorption and decreased damage resistance, whereas contamination by a single particulate during the coating process can lead to a failed optic.
5. Surface finishing is an important step in the process of optic fabrication. Stresses imposed during finishing can either strengthen (*e.g.* via strain hardening) or weaken (*e.g.* by detachment) the surface.

Our results indicate that grazing incidence metal mirrors can meet the requirements on laser-induced damage for long-term exposure in a power plant final optic. Solid solution alloy mirrors appear to offer significant advantages over pure Al. Experiments to date have demonstrated the improved performance at lower shot counts. Improvements to the coating technique are expected to demonstrate higher fluence capabilities soon.

ACKNOWLEDGMENTS

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