Damage Threats and Response of Final Optics for Laser-Fusion Power Plants

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The final optics for laser-IFE (inertial fusion energy) power plants will be exposed to a variety of damage threats, including high-energy neutrons and gamma rays, x-rays and ions from the target explosion, contamination by condensable gases and particulate, and the laser itself. Experiments and modeling have been performed in order to understand damage mechanisms and possible solutions for those threats that are judged to be the most serious concerns for a power plant.

1. Introduction

Survival of the final optic is one of the most critical issues for a laser-driven IFE power plant. Laser-induced damage is compounded by the presence of contaminants and various prompt radiations that emanate from repeated target explosions. Table I summarizes the various damage threats and also provides nominal goals for a power plant. These goals are driven by the desire for modest-sized optics (operating at ~5 J/cm^2 fluence), lifetime on the order of years, target physics requirements imposed on beam characteristics, and acceptable cost-of-electricity. Direct drive targets require illumination symmetry of the order of 1% and positioning accuracy of 10-100 μm.

Table I. Damage threats and nominal goals

Final Optic Threat	**Requirement**
Defects and swelling (γ-rays and neutrons)	Absorption loss <5% Wavefront distortion < λ/2
Optical damage by laser (LIDT)	>5J/cm^2 threshold (normal to beam) for >10^8 shots
Contamination	Absorption loss <5% >5 J/cm^2 damage threshold
Ablation by x-rays	<10^{-4} monolayer per shot
Sputtering by ions	<10^{-4} monolayer per shot

For transmissive optics, radiation-induced darkening is a particularly serious concern. Highly pure SiO_2 and CaF_2 have been irradiated and the increased absorption coefficients arise from known color centers. The possibility of reducing the damage through annealing at elevated temperature has been evaluated.

For reflective optics, the primary design option considered is grazing-incidence metal mirrors. For these, the most serious concern is reduction in laser damage threshold due to long-term exposure and contamination. Unstable surface deformations due to operation at grazing incidence angles are possible and have been evaluated. Both experimental results on LIDT and modeling of defects are presented.

2. Neutron damage to transmissive optics

After n^{o}-irradiating fused silica samples for a IFE-equivalent dose of several months at several temperatures (performed at LANSCE, Los Alamos), the optical absorption spectrum plotted in Fig. 1 is obtained. For the case of irradiations at 105 ˚C and 179 ˚C, the spectra nearly overlap (sample path length of 1 cm). The peak at 630 nm is due to Non-Bridging Oxygen Hole Centers (NBOHC), while the rising edge at 350 nm arises from Oxygen Deficient Centers (ODC) [1]; the slow rise in the sample irradiated at 425 ^{o}C is due to scattering. The mechanism illustrated in Fig. 2 explains the experimental observations, including the fact that the ODCs and NBOHCs are created in roughly equal numbers, γ-rays form E' centers from the ODCs, and the defects can be thermally annealed away. The annealing is illustrated in Fig. 3, where the defects in the sample originally n^{o}-irradiated at 105 ^{o}C are shown to return to its original state at 380 ^{o}C. In addition, a type of "radiation annealing" is observed to occur, which leads to a maximum absorption coefficient of ~1 cm^{-1} at 350 nm, irrespective of dose. This process operates because the collisional cascades overlap at high dose, and a maximum level of defects forms. The plausibility of employing thin (<1 mm) fused silica as the final optic is being explored.

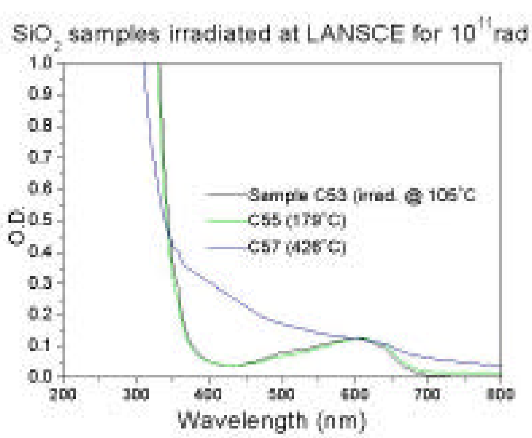

Fig. 1. Results for irradiating fused silica for ~ 10^{11} rads at the indicated temperature.

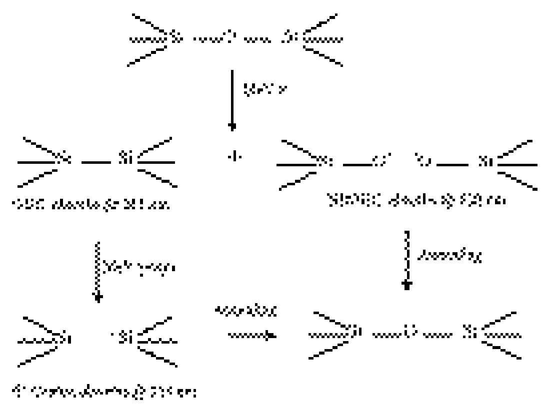

Fig. 2. Mechanism by which neutron-irradiation of SiO_2 leads to the formation of Oxygen Deficient Centers (ODC) and Non-Bridging Oxygen Hole Centers (NBOHC).

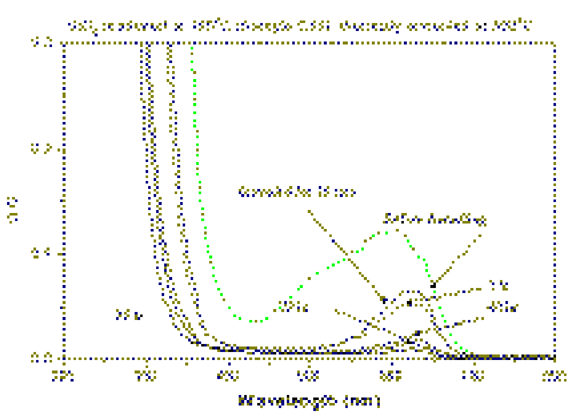

Fig. 3. Thermal annealing of the NBOHCs (near 630 nm) and the ODCs (edge observed at 300–350 nm).

3. Laser-induced damage to grazing incidence mirrors

For KrF lasers, color centers near the operating wavelength of 248 nm may rule out transmissive final optics. Very high performance is possible using multi-layer dielectric mirrors; however, fears over the effect of neutron-induced damage have led to the adoption of metal mirrors as the primary candidate [2]. Unfortunately, metal mirrors suffer from relatively low reflectivity (and consequently low damage threshold), especially for UV wavelengths. Aluminum maintains relatively high reflectivity for UV light. By operating at a grazing angle of incidence with s-polarized light, reflectivities in excess of 99% are possible.

One of the unresolved issues for grazing incidence metal mirrors is whether or not they can operate for long periods of time at laser fluences higher than the normal incidence damage threshold (for aluminum this can be as low as 0.2 J/cm^2). In order to keep the optic size modest, a goal of 5 J/cm^2 normal to the beam was chosen as a reasonable goal. Although laser-induced damage to metal mirrors has been explored previously, uncertainties still exist in the fundamental mechanisms of LIDT for multiple-shot beams, the influence of erosion (sputtering, pitting and cratering) mechanisms, and possible changes in the mechanical properties by pulsed neutron irradiation. Modeling of unstable thermomechanical deformations of metal surfaces was performed in order to predict the long-term damage threshold. In addition, experiments were performed on diamond-turned Al surfaces at 85° angle of incidence for up to 10,000 shots in order to provide experimental validation.

3.1 Modeling of grazing incidence metal mirror damage

Structural changes induced by a laser beam occur in the crystal lattice subsystem of the material, which can be considered as an elastic continuum. On the other hand, laser radiation excites only the electronic subsystem, creating a non-equilibrium plasma state in a shallow layer of the material. Relaxation of this sub-surface plasma leads to intense local heating and generation of a variety of lattice (point and extended) defects. These point and extended defects (*e.g.*, dislocations) - viewed as rigid inclusions in the elastic continuum - will thus deform it.

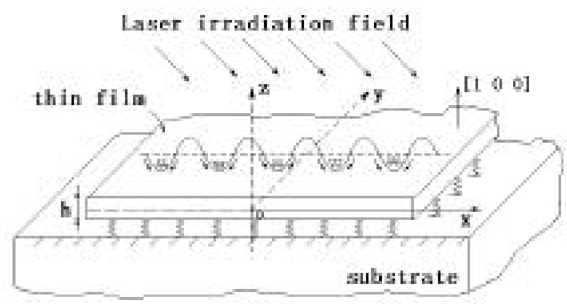

Fig. 4. Schematic of the model for laser-induced surface instabilities and the formation of "ripple" patterns.

Experimental evidence for the formation of point and extended defects in laser-irradiated materials were first reported in the early seventies by Metz and Smidt [3,4]. The deformation of the elastic continuum itself changes the transport characteristics of these defects in such a way as to minimize the total free energy of the system. An unstable feedback loop is set up, driven by laser irradiation, and controlling the interaction between the defect and deformation fields of the material, as illustrated in Fig. 4.

We developed a model which describes the dynamics of such systems in the case of uniform laser irradiation [5]. We also extended this model to the case of focused laser irradiation [6]. The model applies well to the description of the mechanical deformation behavior of thin coatings on substrates (as in coated laser optics), and is in very good agreement with experimental data. Through linear, nonlinear and numerical analyses, we determined how rose deformation patterns, with petal number increasing with laser intensity, naturally arise in this model, in agreement with experimental observations on focused laser irradiation, as can be seen in Fig. 5.

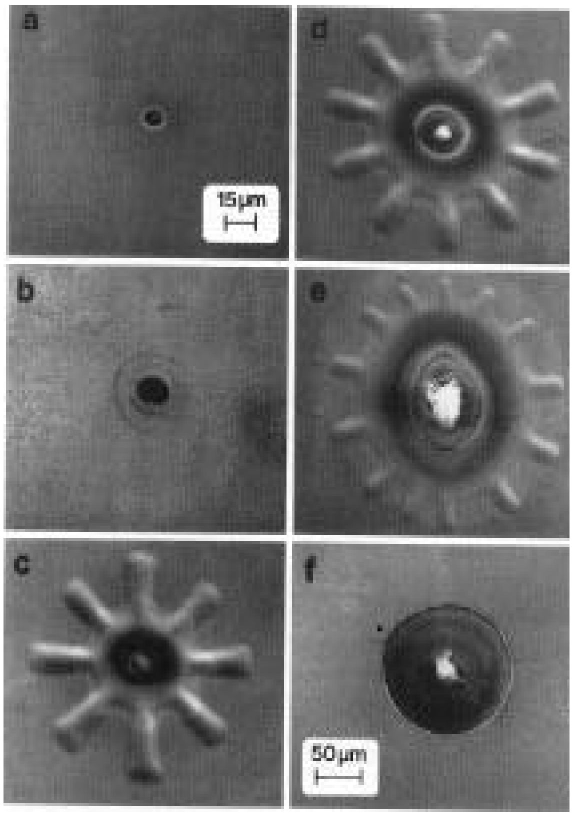

Fig. (5a): experimental observations of "Rose' deformation patterns in focused laser [7].

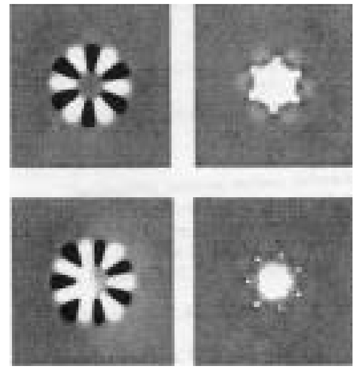

Fig. (5b): Computed "Rose" surface deformation [6].

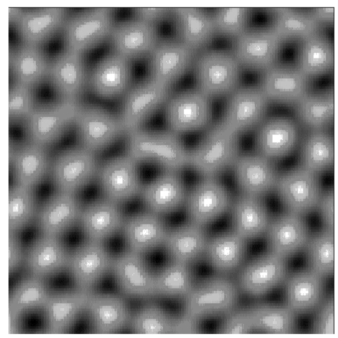

Fig. (5c): Results of numerical solutions for surface deformation patterns in laser-irradiated surfaces [5].

3.2 Experimental data on grazing incidence metal mirror damage

Experiments were performed using a frequency-doubled YAG laser with a beam size of 1.2 cm and maximum energy of 800 mJ. Mirrors were fabricated by diamond turning 99% pure (Al-1100) and 99.999% pure aluminum with a natural oxide coating ~30 nm thick. An example undamaged surface profile is shown in Fig. 6. The lathe marks are clearly evident, with a maximum surface height variation of ~30 nm.

Experiments were performed for single and multiple shots up to 10^4, all at 85° angle of incidence. The Al-1100 mirrors survived single shot exposure up to 18 J/cm^2 normal to the beam. Below 8 J/cm^2 no visible damage is observed up to the maximum number of shots tested. Between 8-18 J/cm^2, visible changes appear on the surface, indicating the onset of microscopic damage. After continued exposure at this fluence level, the damage grows and may become sufficiently severe to cause enhanced absorption and eventually ablation (see Fig. 7). Fig. 8 summarizes damage measurements for Al-1100. For comparison, Fig. 9 shows the response of a pure Al surface which survives up to the melting threshold without exhibiting an intermediate damage regime. Pure Al appears to have a significantly increased damage threshold as compared with Al-1100. Experiments are ongoing.

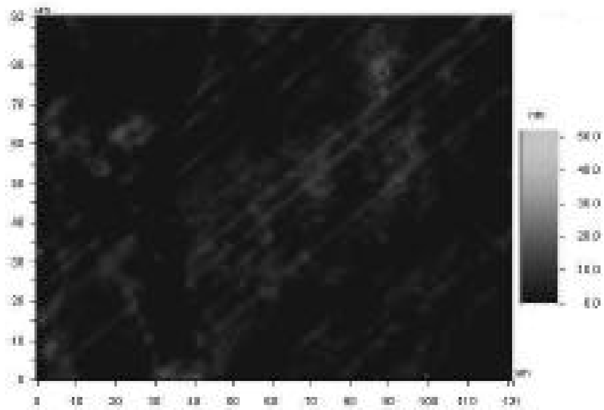

Figure 6. Surface profile of an undamaged Al-1100 mirror

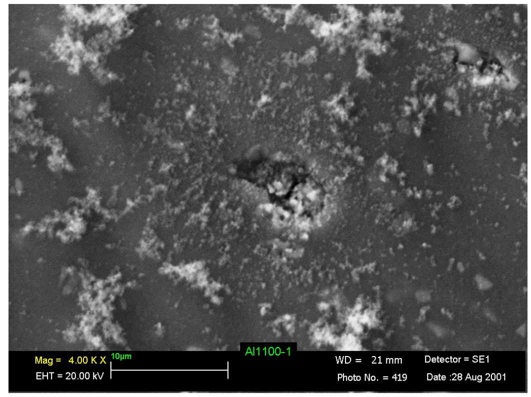

Figure 7. SEM photo of Al-1100 mirror exposed to 20 J/cm^2 for 10^4 shots

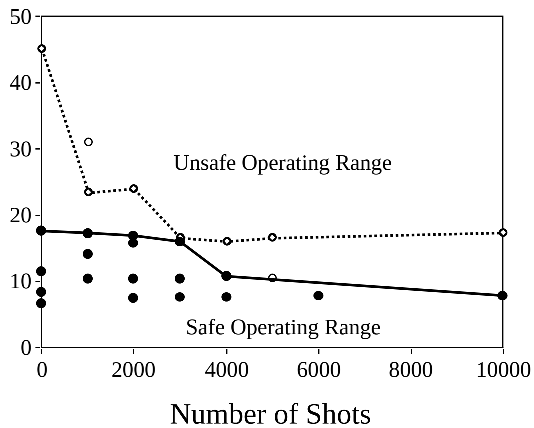

Figure 8. Damage regimes for Al-1100

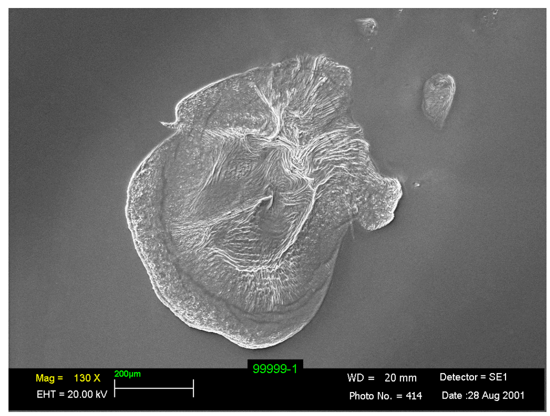

Figure 9. SEM photo of pure Al exposed to one shot at 180 J/cm^2

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