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Lifetime survivability of contaminated target-chamber optics

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ABSTRACT

Target chambers used for Inertial Confinement Fusion (ICF) expose laser optics to a very hostile environment not only from high-fluence laser irradiation but also x-ray irradiation and particulate debris from targets and chamber wall materials. Expendable debris shields provide the first line of defense to more costly optics upstream in the laser beam path to contaminants generated within the target chamber. However, the replacement of a large number of debris shields is also an expensive proposition so that extending their usable lifetime within the chamber is of crucial importance.

We have conducted tests to show that optics can both be cleaned and damaged by laser irradiation at 355 nm after being contaminated with potential chamber-wall materials such as B_4C and Al_2O_3 . Such optics can survive from one to hundreds of laser shots depending on the degree of contamination and laser fluence levels. Similarly, we have studied the survivability of optics that have been exposed to direct contamination from representative target materials irradiated in the target chamber. We have also studied the effects on optics that were not directly exposed to targets yet received secondary exposure from the above directly-exposed samples.

Keywords: B_4C , contamination, first-wall material, laser damage, lifetime, target chamber

1. INTRODUCTION

The National Ignition Facility (NIF) is the next generation of high power lasers being developed for the study of Inertial Confinement Fusion (ICF) by a consortium of laboratories consisting of the Lawrence Livermore National Laboratory (LLNL), the Los Alamos National Laboratory, the Sandia National Laboratory, and the Laboratory for Laser Energetics at the University of Rochester. The 192-laser-beam facility will be capable of depositing 1.8 MJ of 351-nm laser energy on target. Commensurate with the large size of the laser facility, the target chamber will be 10 m in diameter. Final optics in the target chamber will be subjected to average and peak laser fluences of 8 and 12 J/cm² respectively for 3-ns-equivalent pulses at 351 nm. In addition, the optics, diagnostics and inside wall (first wall) of the target chamber will be subjected to target debris, 14-MeV neutrons, and 200-eV blackbody x-rays. Further contamination may ensue from vacuum-chamber outgassing, chamber venting and in-situ cleaning such as with particulate CO₂. The magnitude for potential contamination can be grasped when one considers that a uniform ablation of even a 0.1-μm thickness of material from the target-chamber first wall will redeposit a total of 30 cm³ of material on all target-chamber components (Fig. 1).

We have conducted studies at LLNL to evaluate the effects of some of these phenomena on first-wall materials of the target chamber, and optics that have been exposed to them. In particular, we have examined (1) the lifetime survivability of fused-silica substrates that have been pre-exposed to varying degrees of contamination from candidate first-wall materials B_4C and Al_2O_3 ; and (2) both bare and solgel-coated, fused-silica substrates that have been exposed to high-fluence x-rays and target debris in the Nova target chamber at LLNL.

2. FIRST-WALL MATERIAL EVALUATION

2.1 Experimental conditions

In Fig. 2 we show the experimental configurations for exposing fused-silica substrates to first-wall material contamination and subsequent damage testing. Contamination was conducted in a vacuum chamber using the Optical Sciences Laser (OSL) at LLNL. A 351-nm laser beam was transmitted through the substrate to a first-wall target material which ablated material back on the substrate. The degree of single-shot contamination was controlled by the laser fluence, the distance between the target and substrate, and the number of times that a given area on the target was irradiated. Up to four areas, each > 10 mm in diameter, were exposed on the substrates. Damage tests on the substrates were conducted with the Chameleon laser at LLNL using 3-ns pulses at 355 nm with gaussian spot sizes up to 1.2 mm in diameter at the $1/e^2$ level. In most cases the laser was fired one pulse at a time for roughly the first 100 shots. Subsequent exposures, up to as many as 1200 shots, were conducted at repetition rates of 2 or 10 Hz. The samples were irradiated at 5° incidence with P-polarized light. We examined the test surfaces with both dark-field and bright-field illumination at magnifications of 50x and 100x. Typically, the contaminated surface was oriented as an exit surface to simulate the conditions of a target-chamber debris shield (i. e. the interior surface of the debris shield in a target chamber would experience most of the direct contamination in actual practice and would be the exit surface for a laser pulse entering the chamber).

Fig. 1. The target chamber is a hostile environment for laser optics. Target and first-wall ejecta cause damage and form nucleation sites for subsequent laser-induced damage.

Fig. 2. A fused-silica substrate was contaminated by first-wall target material with the Optical Sciences Laser. The sample was damage tested with the Chameleon facility at 355 nm.

Fig. 3. Initial laser shots at an average fluence of 8.5 J/cm² with 3-ns pulses at 355 nm removed B₄C contamination from a fused-silica substrate. After five shots damage pinpoints on the order of 10 μ m in size began to appear and ultimately merged into massive damage with more shots.

2.2 Test sample irradiations

In Fig. 3 we show the effects of a sequence of twenty laser-damage-test shots using 3-ns, gaussian pulses at 355 nm. They were taken on the rear surface of a fused-silica substrate with a relatively high level of contamination of B_4C . The contamination was generated by splatter from a hot-pressed sample of B_4C , situated about 3 mm from the rear surface of the test substrate, using a single 2.5-ns laser pulse at 351 nm with a fluence of 0.6 J/cm^2 . The pre-irradiation surface morphology is shown by the upper left image. The peak of the gaussian laser pulses had an average fluence of 8.5 J/cm^2 . After the first shot most of the B_4C was “cleaned” off and subsequent shots continued with the cleaning process. However, by the fifth shot, some obvious new pinpoints, about $10 \mu\text{m}$ in size, appeared. These grew in size and number with each successive shot so that they ultimately merged into large damage spots into the substrate bulk material after about 10 shots. In general, cleaning would always occur with the first few shots and debilitating damage would manifest itself after one to several hundred shots, depending on the degree of contamination and the level of laser fluence.

Fig. 4. Comparison of surface morphologies of contaminated substrates before irradiation and after twenty shots at ~ 4.3 and 8.6 J/cm^2 with 3-ns pulses at 355 nm.

Fig. 4 shows a summary of surface morphologies of contaminations before irradiation and after twenty shots at average fluences of both 4.3 and 8.6 J/cm^2 . The B_4C -exposed substrate was tested once with contamination on the incident surface and once on the exit surface; the Al_2O_3 -exposed substrate was tested only with contamination on the exit surface. In each case the contamination was generated by splatter from the respective material, situated about 3 mm from the rear surface of the test substrate, using single 2.5-ns laser pulses at 351 nm with a fluence of 0.6 J/cm^2 . In all cases we observed cleaning with no significant damage at the lower fluence exposures but major damage when the fluence levels were doubled. Although the Al_2O_3 -exposed sample displayed marginally less severe damage after twenty shots, alumina was ultimately rejected as a candidate for a first-wall material because of the higher level of x-ray-caused ablation measured under comparable irradiation conditions.

Besides comparing two types of contaminants and the surfaces on which they were deposited, we also conducted some other tests to determine if the severity of damage could be reduced. Improvements in damage thresholds have routinely been observed in both coated optics such as high reflectors and in bulk material such as KDP when pre-conditioned with lower levels of laser irradiation below the unconditioned thresholds.^{1, 2} Similar tests were conducted on B₄C-contaminated substrates. However, after a comparable number of high-fluence shots we observed no decrease in the severity of laser damage compared to unconditioned sites. We also observed that a superficial cleaning of the contaminants with ethanol drag wipes before damage testing was not sufficient to have any effect on either increasing the damage thresholds or reducing the degree of damage. It remains to be determined if particulate CO₂ cleaning of a contaminated substrate will restore the threshold to its pre-contamination high level, although the cleaning process may already induce damage to the optic.

Fig. 5. The severity of damage for a substrate mildly contaminated with B₄C increases with the laser fluence level, the number of shots and the irradiation repetition rate.

A typical summary for all of the tests conducted on a given sample (mildly contaminated with B₄C) is shown in Fig. 5. The contamination was generated by splatter from the fifth shot on a hot-pressed sample of B₄C, situated 50 cm from the rear surface of the test substrate. We used a single 2.5-ns laser pulse at 351 nm with a fluence of 0.6 J/cm². The figure shows four sets of damage tests. Columns represent laser fluences for 20 to 600 shots conducted under the severe test conditions of 10-Hz, repetition-rate irradiation; the circles represent from one to 110 single shots, and ultimately 600 and 1100 shots at a 2 Hz repetition rate. The first set of measurements were for an equivalent, bare, uncontaminated, reference sample which showed that the substrate itself was good enough to have survived fluences of 15 J/cm² at 10-Hz irradiation. Site 1 of the contaminated sample displayed no damage at fluences near 9 J/cm² for more than 100 shots, and then only minor damage after 600 shots. At fluence levels of ~ 13 J/cm² for Site 2, we first observed minor damage after five shots which grew to a greater number of pinpoints after 10 shots and ultimately to major damage after 110 shots. The final region in the figure shows that even under severe 10-Hz irradiations the sample only showed major damage after 400 shots at 10 J/cm².

Fig. 6. Laser damage morphologies, lifetimes and thresholds of substrates depend on the degree of contamination with B_4C . The pairs of pictures above each plot of damage-test data points correspond to the two highlighted shot numbers for each of the four sets of tests. The pictures for test H1310 are shown at 42x magnification; all others are at 21x magnification.

In a qualitative sense we have compared the damage morphologies of substrates with varying levels of contamination of B_4C . These are summarized in Fig. 6. The contaminations were generated by splatter from the target material by single laser shots of 2.5-ns pulses at 351 nm. The contamination levels and the conditions under which they were generated were classified as follows:

Test number	Contamination level	Target to substrate distance (cm)	Fluence (J/cm^2)
H1310	mild	50	0.6
H1313	moderate	50	1.4
H1312	major (near perimeter)	5	1.4
H1311	vaporization (near center)	5	1.4

The fourth level of contamination was for the case in which the ablated B_4C material was actually vaporized so that it was deposited as a film rather than in particulate form. From optical-density measurements the estimated thickness of this film was about 65 Å. The upper picture in each case represents the morphology after a low number of laser-damage shots. The lower pictures show how damage progressed after more shots. The actual laser shot sequence is shown below each pair of pictures. The highlighted shot numbers at the bottom correspond to the shot numbers for the photographs above. In the first two instances, major damage was observed after 110 and 20 shots respectively. The third sample, with major contamination, also showed major damage, but

its morphology consisted of hundreds of tiny pinpoints rather than progressively growing massive craters. Functionally such damage can still be acceptable if it does not grow to massive dimensions. The final sample displayed major ablation of the vapor-deposited B_4C material.

2.3 Summary for first-wall materials

Some contamination of laser optics in a NIF target chamber due to the ablation of chamber, first-wall material is certain. This will particularly be the case for the interior faces of the fused-silica debris shields which are the final optical surfaces of the laser beam lines. We have conducted extensive testing on a variety of environmentally safe first-wall candidate materials. The physical requirements were that they have high abrasion resistance from target shrapnel and cleaning processes, low vacuum outgassing, and low levels of ablation due to x-ray and laser light irradiation.³ We conducted damage tests on two leading candidate materials, B_4C and Al_2O_3 , that when splattered on fused silica substrates, provided the least amount of visible contamination to the substrates. With low to moderate contamination by either material we observed tolerable levels of damage. However, for comparable laser irradiations during the contamination stage, the level of contamination from B_4C was less dense than that from Al_2O_3 .

At fluence levels of $\sim 4 \text{ J/cm}^2$ for irradiation with 3-ns pulses at 355 nm we observed minimal, if any, damage to all contaminated substrates for hundreds of shots. The most obvious observed effect was that most of the contaminating particulates actually cleaned off. When the fluence levels were doubled to $\sim 8 \text{ J/cm}^2$ isolated pinpoints, on the order of $10 \mu\text{m}$ in size, were observed after about five shots for mild contamination and just one shot for major contamination. Functionally such damage morphology would per se have no major impact on transmitted laser light. However, these pinpoints became nucleation sites for further damage growth with successive shots. Typically such damage would grow an order of magnitude in size after more than 100 shots for mildly contaminated samples and 10 to 20 shots for moderate to major contamination. At fluence levels of $\sim 13 \text{ J/cm}^2$ (which exceed the 12-J/cm^2 peak fluence levels of NIF) damage would occur on the first shot but would not grow to critical levels until after three to ten shots depending on the degree of contamination. In all cases we observed more severe damage when the contaminated surface was the exit surface as compared to the entrance surface. As a point of reference, under comparable irradiation conditions, clean, superpolished fused-silica substrates have rear surface thresholds in the range of 15 to 20 J/cm^2 .

In-situ cleaning of contamination by a variety of techniques proved to have little impact on improving damage thresholds. Ethanol drag wiping yielded cosmetically cleaner looking surfaces but failed to remove sufficient contamination to raise thresholds. Laser conditioning with gradually increasing laser fluences did provide superficial removal of particulates, but subsequent irradiations with higher fluence shots yielded damage comparable to sites that had not been conditioned. Although CO_2 -particulate cleaning might prove beneficial for some in-situ cleaning of first-wall materials, contaminated substrates would probably be damaged by this cleaning process.

3. EXPOSURE TO X-RAYS AND TARGET DEBRIS

3.1 Experimental conditions

In order to establish the effects of x-rays and target debris on NIF target-chamber optics, we subjected both bare and solgel-AR-coated substrates directly to Nova laser targets (Fig. 7). Maximum x-ray fluences at the 5-m radius of the NIF target-chamber wall may be as high as 2.5 J/cm^2 for high-yield target shots. To simulate these conditions we positioned the substrates 22 cm from the Nova targets to obtain 200-eV-blackbody x-ray fluences up to 3.5 J/cm^2 . One third of each sample area was blocked from direct line-of-sight by a stainless-steel plate. Bare collecting substrates, which were completely blocked from direct x-ray exposure by the stainless-steel plate, were used to collect ablated material from the directly exposed substrates. Half of each collecting optic was covered by a plastic foil. All direct and collector optics exhibited a high density of plastic and metallic target debris, primarily gold, copper and aluminum. In the upper picture of Fig. 8 we show an example of the high density of debris that even collector optics exhibited before off-line laser damage testing. The lower pictures show removal of some of this debris and the formation of substrate damage after 1 and 20 laser shots.

Fig. 7. Bare and solgel-AR-coated fused silica substrates were exposed to Nova laser-target debris and x-ray fluences up to 3.5 J/cm^2 . One third of each sample was obscured from direct line-of-site by a beam block. A collector substrate, half obscured by a CH foil, collected second-hand debris. Damage testing with Chameleon was conducted in the same fashion as for the first-wall samples.

Fig. 8. The exposed half of a collector test sample that faced a bare fused-silica substrate in Nova had much debris which cleaned off with 355-nm laser irradiation but eventually damaged.

3.2 Test sample irradiations

Two series of experiments were conducted exposing bare and solgel-AR-coated fused-silica substrates to Nova target shots. Representative data are shown in Fig. 9 for a bare substrate facing the Nova target. The left portion shows data for a region that was blocked from direct line-of-sight by a metal plate in front of the optics fixture. The central portion shows data for a region directly exposed to one shot but blocked from a second Nova shot. The right portion was exposed to two Nova target shots. All sites were heavily contaminated with target debris, which in the case of the exposed sites, yielded many pinpoints of damage after only one to five shots at fluence levels of 4 J/cm^2 . All sites, including those blocked from the direct line-of-sight of the Nova target, also showed significant cleaning with low-fluence laser damage-test shots. Major damage ensued in all cases at fluence levels between 7 and 9 J/cm^2 . However, the lowered damage threshold was probably not related to the x-ray exposure. Instead, it was probably determined by the large amount of microscopic metallic debris from the Nova target. Although optics in the NIF target chamber might be exposed to comparable high-fluence x-ray exposures at a distance of 5 m from a NIF, high-yield target, the density of target debris would be significantly less than that obtained from a Nova target at a distance of only 22 cm.

Fig. 9. All sites exposed to Nova laser targets exhibited laser damage after only one to five shots at 355 nm due to target debris accumulation. All sites, even those blocked from direct line-of-sight to the target, developed major damage at fluences of 7 to 9 J/cm^2 .

The bare collector sample, which was exposed only to material ablated from the exposed optic, fared even worse. The dark-field microscopy shown in Fig. 8 shows substantial particulate contamination. In addition, visual inspection of the optic in reflection indicated the presence of a thin film deposit on the portion closest to ablating optic. Subsequent spectrophotometry found enhanced UV absorption in that area. The region not

Fig. 10. The exposed half of the collector test sample that faced the fused-silica substrate shown in Fig. 9, but was not directly exposed to the Nova laser targets, fared even worse with major damage at 355-nm fluence levels between 4 and 8 J/cm².

covered by the plastic foil began to damage at levels of 4 J/cm² after 10 shots and with the first shot at levels above 5 J/cm², as shown in Figure 10.

We were able to determine that x-ray ablation of both the bare-substrate material and the solgel-AR coating did not adversely affect the figure of the optics. In Fig. 11, we show an interferometer scan of a bare substrate. The right half was exposed to two Nova target shots with x-ray fluence of 3.5 J/cm²; the left half was protected by the fixture beam block. Although over 200 nm of material were removed from the substrate, the removal was uniform, with no change in the substrate figure.

3.3 Summary for target debris and x-ray exposure

The lifetime survivability of optics to high fluence x-rays and target debris from NIF target shrapnel has not been completely resolved. In order to obtain x-ray fluences as high as 3.5 J/cm² in the Nova target chamber we have been required to expose bare and solgel-AR-coated test substrates to target debris only 22 cm from the targets. The high density of target debris was far in excess of what would be observed in a NIF target chamber at a 5-m radius, yet it totally dominated threshold measurements on both directly and indirectly exposed substrates. We observed debris-initiated damage at fluences as low as 4 J/cm² for 3-ns pulses at 355 nm within one to five shots. This damage became major at fluence levels of 7 to 9 J/cm². We did observe a uniform ablation of substrate and solgel material due to the direct x-ray exposure of one or two Nova target shots. Although in excess of 200 nm of material was removed from the test samples, the removal was uniform with no detrimental effect to optical figure of the samples. With such effects on NIF debris shields, they should readily be able to survive 10 to > 100 shots high-yield target shots.

Fig. 11. Exposure to two shots of ~ 200 eV blackbody x-rays at 3.5 J/cm^2 in the Nova laser target chamber ablated more than 200 nm of material (right half of bare, fused-silica sample) but did not change the surface figure.

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