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X-RAY RESPONSE OF NATIONAL IGNITION FACILITY FIRST SURFACE MATERIALS

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ABSTRACT

The ablation of first surface materials by x-rays is a primary threat to the final optics in the NIF target chamber. To meet the operational goals of the facility, the designs of the chamber wall, target holder, and diagnostic surfaces must minimize ablation by x-rays, typically by specifying materials that are low-Z, high temperature resistant, and shock resistant. Additionally, the response of the optics to direct target emissions must be understood. This paper describes some experimental and modeling work to develop the validated computer models necessary to quantify the x-ray response of various materials. These codes and further experiments will then confirm the ability of NIF first surface designs to meet functional requirements.

INTRODUCTION

The Department of Energy is proposing to construct the National Ignition Facility (NIF) by the year 2001 to embark on a program to achieve ignition and modest gain in the laboratory. The NIF will use 1.8 MJ of 0.35 μm laser light, nearly a fifty-fold increase in energy over the Nova laser at LLNL. A 5 m radius spherical aluminum chamber will contain the target experiments and allow access to diagnostics for data collection.

The ablation of first surface materials by x-rays is a primary threat to the final optics in the NIF target chamber. (Here first surface means any surface on the chamber, diagnostics, or other internal structure that receives direct radiation from the target.) If the laser optics become coated by more than a few Angstroms of condensed material, subsequent laser pulses will damage the optics. The coating accumulation rate must therefore be low enough to accommodate the planned shot total between weekly cleaning cycles. To achieve this goal, the designs for the chamber wall, target holder, and diagnostic surfaces must minimize ablation by x-rays. Typically the solution will involve the use of coatings of low-Z, high temperature materials. Additionally, the response of the optics (specifically the debris shields) to direct target emissions and chamber debris must be understood. The goal of this work, therefore, is to develop and experimentally validate accurate computer models of the entire process of ablation and chamber dynamics.

DESCRIPTION OF MODELS

X-ray deposition occurs in the first few microns of a material for the typical spectrum found in the NIF chamber (roughly equivalent to a 300 eV blackbody). The resulting steep profile of energy deposition versus depth can create melting or vaporization of the very front surface, even with energy fluences below 1 J/cm^2. Since the energy deposition occurs almost instantaneously (within a few nanoseconds), large pressures can develop as the hot material expands. The pressure drives the ablated material off the surface at high velocity, and sends shock waves into the bulk material.

Modeling of x-ray ablation includes energy deposition, thermodynamics of phase change, and dynamics of shock and material motions.[1] The x-ray deposition calculation is the most straightforward, in that published tables of photon cross-sections and material thermal properties can generally be used at the fluences of interest (less than 10 J/cm^2). The given input spectrum is divided into numerous groups, and the energy and absorption for each group are tracked through the material. The total energy at any depth is just the sum over all energy groups.

$$e(x) = \sum_{i=1}^{n} \frac{I_o(i)}{\lambda(i)} \exp\left(\frac{-x}{\lambda(i)}\right)$$

$I_o(i)$ = incident energy in group i

$\lambda(i)$ = photon mean free path for group i

Thermal conductivity can usually be neglected because of the very short time scales for energy deposition and subsequent material motion.

The processes involved in the phase change over these short time scales (a few nanoseconds) and length scales (a few microns) are the quite complex. The energy deposition profile may provide sufficient energy to vaporize material on the front face, while merely warming material at greater depths. This means that some regions will have more than the energy necessary to reach the boiling (or melting) temperature, without having enough energy to be fully vaporized (or melted), if the full latent

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heat is not added. Therefore some two-phase regions may be created once the high initial pressure relaxes. These regions may have transport properties much different from either single phase. This will affect the material motion, which will in turn affect the state of the two-phase zone, creating the need for an iteration scheme.[2] However, the current model uses a much simpler assumption. The divisions between vaporized, melted, and solid zones are taken to be sharply defined (that is, without two-phase regions). This assumption has unknown implications on the accuracy of predictions for material removal depths, velocities, and subsequent condensation.

The steep gradients in energy deposition lead to equally steep gradients in pressure, which in turn develop into shock waves. Since the surface is at essentially zero pressure, a rarefaction wave develops immediately after the energy pulse as well. This wave rapidly reduces the strength of the shock preceding it into the material. As a result, after only a few millimeters, the shock is generally weak enough that it will not cause damage. Shock damage generally only has the potential to occur in thin sheets of material or in the protective coatings used on exposed surfaces. The possible failure of thin coatings and films under x-ray loading can be assessed with shock propagation models. Preliminary calculations do show, however, that the plasma-sprayed coatings will survive, partially because their porosity improves shock attenuation.[3]

Material vaporized by the x-ray fluence will travel outward from the wall. It will interact with chamber structures, target debris, and vapor from other parts of the chamber. This vapor will obey the equations of motion for inviscid fluids (Euler equations). The TSUNAMI gas dynamics model can be used to track this flow of vapor mass and energy.[4] Three types of boundary conditions are possible, depending on the assumption used for condensation of the vapor. A closed boundary reflects all incoming gas, which provides the noncondensable case. This is useful for determining upper limits of pressure. An open boundary allows free passage of all gas, which is equivalent to the perfect condensation. Tracking the mass flow out the boundary cells gives a prediction of the distributions of debris energy and condensed materials within the target chamber or other structures. A third boundary condition includes a simple model of condensation to give behavior between the first two limits. This feature has not yet been fully implemented in the code.

MODELING RESULTS

The relevant x-ray sources for this study are laser generated plasmas. Both the existing Nova facility and the NIF will produce an x-ray spectrum that approximates that of a blackbody at a temperature of about 300 eV. This spectrum has a peak power near 1 keV.

The fluences and pulse length studied reflect the expected output of the baseline NIF hohlraum driven by 1.8 MJ of laser energy, with target yields from 0 to 20 MJ. The x-ray fluences at the first wall (5 m from the target) range from 0.3 to 1.8 J/cm^2. A fluence range of 0.2 to 0.9 J/cm^2 is expected at 6.5 m from the target at the locations of the debris shields. The range of fluences on the first wall for any target arises from the various target yields and the assumption of a Lambertian-like (cosine) distribution of the x-rays emanating from the hohlraum's laser entrance holes. The range in the debris shield fluence is a consequence of this distribution on the two different cone angles on which the beams are located. These values assume that 50% of the laser energy is converted into x-rays and the remainder is in debris energy. Likewise, of the 20% of the fusion yield that is not neutrons, half is assumed to contribute to x-rays and half to debris. The pulse length, expected to be several nanoseconds, is taken to be 1 ns for conservatism.

X-ray fluences in NIF would be high enough to ablate a large mass from a bare aluminum chamber wall (hundreds of kilograms per year). This would be a significant problem for the final optics, which would tend to be rapidly obscured by condensed aluminum. In addition, chamber cleanup and decontamination operations would become much more difficult and frequent. Therefore the chamber walls must be protected with a coating of low-Z, high temperature material to minimize x-ray ablation. The coating will be applied (probably plasma-sprayed) onto aluminum panels bolted to the inside of the target chamber. This design allows damaged sections to be replaced without the requirement for in situ plasma spraying work.

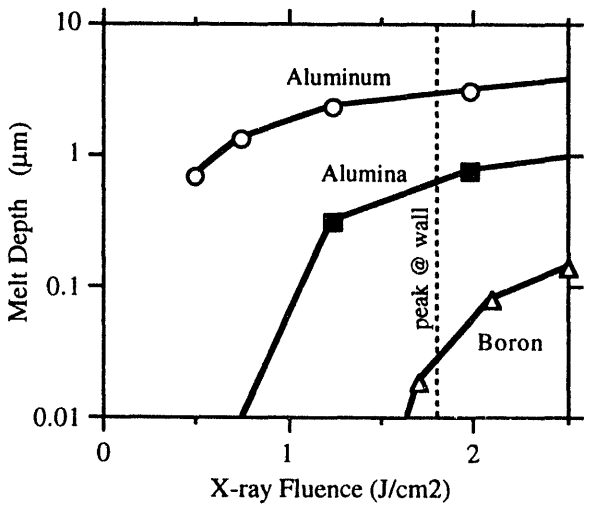

Figure 1: Melt depth of several NIF chamber materials exposed to 350 eV blackbody x-rays.

Figure 1 shows predicted x-ray ablation depths for the bare aluminum wall and two candidate coating materials. Boron appears to offer the best performance for use as the first wall coating, while the alumina would be much less expensive and easier to apply. From the plot, it is evident that either coating will prevent ablation for the shots without yield (x-ray fluence below 0.6 J/cm^2). If the single high yield shot to be performed each week is done at week's end, then some first wall ablation may be tolerated, since the weekly debris shield refurbishment will be performed before more shots are attempted.

The figure also shows a line at the maximum expected fluence at the wall from a 20 MJ shot. This fluence is just at the minimum needed to ablate the boron coating. This provides a basis for the conservative choice of a 5 m chamber radius, which for the most part provides sufficient standoff from the target to prevent x-ray ablation of the walls.

EXPERIMENT DESCRIPTION

Experiments serve two purposes: validation of code predictions and demonstration of first surface material performance at NIF-level x-ray fluences. Code validation involves matching experimentally determined damage thresholds and ablation depths for various materials.

Experiments are being conducted on the Nova laser at Lawrence Livermore National Laboratory. Gold disk targets roughly 1 mm in diameter and 1-2 μm thick are irradiated on each side by 5.2 kJ of 0.35 μm laser light in 1 ns pulses, which gives intensities close to 10^{15} W/cm^2. Forty percent of this energy is converted to x-rays with a spectrum that approximates a blackbody emitting at 250 eV. Samples placed 10 - 80 cm from the target receive x-ray fluences of 5 - 0.07 J/cm^2 and varying target debris fluxes. X-ray fluences at the samples are determined from calibrated, time-resolving spectrometers covering the range from 100 eV to 3 keV.[6]

Debris from the gold target can potentially modify the test results. The total energy in the debris is roughly the same as the total energy in x-rays. One way to deal with this issue is to shield the samples from debris using thin filters. For example, one set of samples was protected by 1.0 or 0.5 mil thick beryllium foils. The problem is that even with thin, low-Z filters a large portion of the x-rays below about 1 keV cannot penetrate. This can change the approximate spectrum from 250 eV to roughly 700 eV, which is no longer a very close match to NIF's 300 - 350 eV spectrum. The other way to deal with debris is to minimize target size to the point where it is totally vaporized by the incident laser beams, yet still convert a large fraction of the energy to x-rays. In this case, the samples are directly exposed to all target emissions. Samples are placed at angles of from 50° to 60° to the target normal to avoid the bulk of the debris mass that presumably blows off normal to the surface.

A portion of each 1.0 - 1.3 cm diameter sample is protected from x-rays with a thin (2 mil) tantalum foil placed on the surface of the sample. This provides a clear demarcation line between exposed and unexposed material, at least in cases with x-ray fluences high enough to affect the surface.

After the shot, samples were examined visually for any obvious damage. SEM and/or AFM scans were also made across the exposed/unexposed boundary to see details of the effects and to determine the step change in surface level caused by ablation.

Samples to be exposed to x-rays are mounted to carts that travel in SIM tubes (six inch manipulator). The Nova SIMs allow the insertion and removal of a number of samples without bringing the chamber up to atmospheric pressure. Approximately six to eight samples can be placed on any one SIM, with various standoff distances to the target. With the use of several SIMs, many different materials can be tested on each shot.

EXPERIMENTAL RESULTS

Figure 2 shows the response of polished silicon exposed to x-rays in Nova. In this test, the samples were located behind either 1.0 mil or 0.5 mil beryllium foil filters. Absorption of the colder x-rays by the filter brought the spectrum to an effective blackbody temperature of 700 eV.

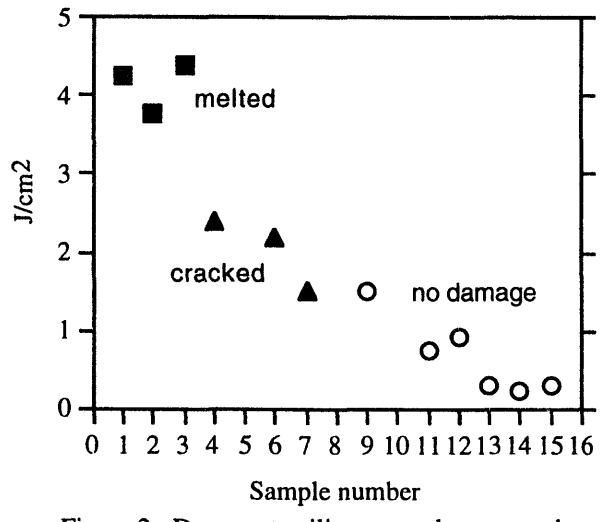

Figure 2: Damage to silicon samples exposed to a 2 ns pulse of x-rays with a spectrum approximating a 700 eV blackbody.

The front surface of the highest fluence samples (4 J/cm^2) appeared rough, indicating that the polished surface layer had melted. Samples that were exposed to

about 2 J/cm^2 still appeared to have the original finish, although the 0.5 mm thick samples had fractured into numerous small pieces. Samples that saw less than 1.5 J/cm^2 were undamaged. Calculated energy depositions indicate that the surface will be brought to melt temperature (about 1400°C) by a 0.9 J/cm^2 x-ray fluence, while complete melt (including latent heat of fusion) is attained with 2.3 J/cm^2. Therefore x-ray response seems to be modeled fairly well, at least at the high and low energy levels. More sophisticated fracture analysis techniques will need to be used to model cracked samples in the intermediate energy range.

Clear plastic films offer the potential for use as a sacrificial barrier between the target and the final optics. Response to x-rays is one of the pieces of information necessary to evaluate usefulness of such films. Several different plastic films were exposed to x-rays in Nova experiments. The materials tested include Teflon AF1600, polyvinyl alcohol (PVA), polymethyl methacrylate (PMMA), and polyvinyl pyrrolidinone (PVP).

Teflon film samples, on the order of 30 μm thick, were exposed to direct target emissions in Nova experiments. The x-ray spectrum was composed primarily of 250 eV blackbody emissions, with about 24% of the total energy in gold M-band emissions in 2-4 keV. The pulse length was 1 ns. The partial tantalum mask over the front surface of the films produced a well-defined edge where the exposed region adjoined the protected surface. Atomic force microscopy (AFM) was used to determine the step height. A typical lineout from an AFM scan is shown in Figure 3. This plot shows that for initially flat samples like the plastic film, ablation depth measurements are possible down to the order of 0.1 μm.

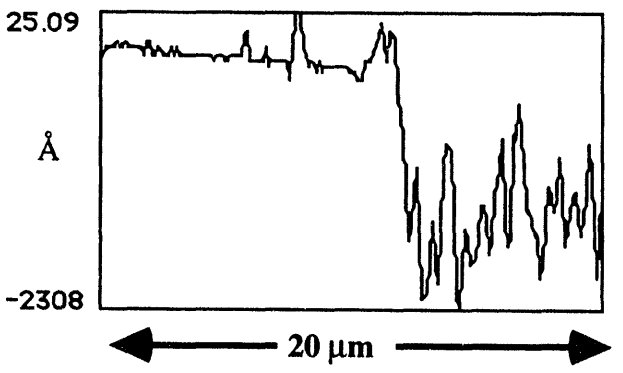

Figure 3: AFM scan of Teflon exposed to an x-ray fluence of 0.11 J/cm^2 on Nova. The average step height for this sample was 0.13 μm (1300 Å).

Figure 4 is a plot of the measured material removal depths for this series of Teflon samples over the range of x-ray fluences. The solid curve on the graph is a prediction of the depth at which the material reaches the melt temperature (330°C). For this case, it appears that the onset of material removal is well predicted by incipient melt energy. The deviation from prediction at the highest fluence warrants additional testing. This difference may be due to the coupled hydrodynamics and thermodynamics in the thicker ablation layers.

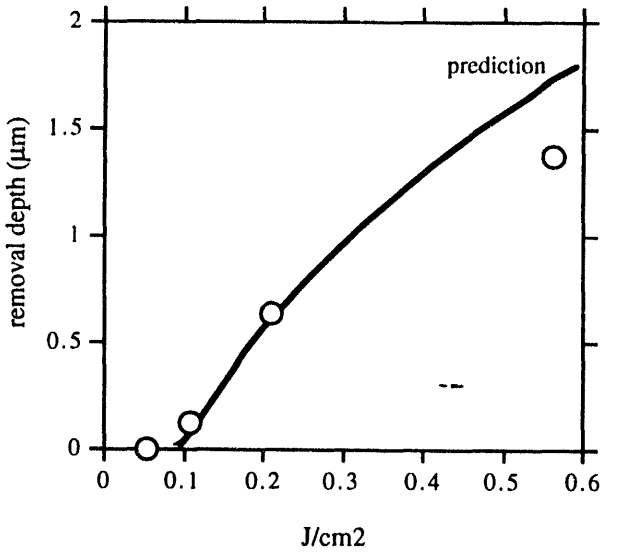

Figure 4: Comparison of measured removal depth with predicted incipient melt depth for Teflon AF1600. Spectrum is 250 eV blackbody plus 24% from gold M-band (2-4 keV).

DISCUSSION

X-ray ablation models used here are based on the straightforward approach of calculating an instantaneous energy deposition profile then predicting blow off based on depth to reach melt energy. These models appear to function well for the weak plastic materials, and as rough guide for the failure of brittle materials. Therefore this approach should be a useful first step in implementing more sophisticated models that include shock propagation, material failure, and the gas dynamics of ablated material.

Additional testing of the x-ray response of candidate NIF first wall materials and optics surfaces are needed to validate the predictive models and to "certify" the usefulness of these materials in NIF. Some of these tests will involve plasma-sprayed coatings of boron, tungsten-loaded boron, aluminum oxide, as well as solid graphite. Materials of interest in NIF optics are fused silica and various anti-reflection coatings that may be employed.

ACKNOWLEDGMENTS

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