Nova Experiments to Investigate Hydrodynamic Instabilities in the Solid State


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Nova experiments to investigate hydrodynamic instabilities in the solid state

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Abstract: Experiments were done to shock compress and accelerate copper foils at peak pressures of ~3 Mbar above and below the melt temperature to study the effects of material strength on hydrodynamic instabilities. An x-ray drive generated in a hohlraum target was used to generate the shock wave profiles. The growth of a preimposed perturbation at an embedded interface is diagnosed by x-ray radiography. Results obtained using a high contrast shaped laser pulse show that the growth of the modulation is delayed compared to fluid simulations, which could be due to material strength stabilization. In contrast, when a copper foil is placed above the melt temperature at >3 Mbar with a single shock, it melts upon compression and the modulation growth is consistent with fluid modeling. Experimental results from copper shocked to 3 Mbar both below and above the melt temperature are presented and compared with simulation.

1. Introduction

In a classical fluid model, when a light fluid accelerates a heavier fluid, the interface is Rayleigh-Taylor unstable. As a result, modulations at the unstable interface will grow. We show the growth is modified by material strength in the solid state.

We are conducting hydrodynamic instability experiments using the Nova laser [1] to study the effect of material strength on shock compressed metal foils. Thin Cu foils are shock compressed with an x-ray drive incident on a brominated plastic ablator to a peak pressure of about 3 Mbar. Using a high contrast (1:25) shaped laser pulse, the foils remain solid, and the material strength appears to reduce the growth of the Rayleigh-Taylor unstable preimposed mass modulation. By contrast, thin Cu foils compressed with a single strong shock melt promptly under compression, and show growth at the interface consistent with fluid modeling.

In this paper, we describe the Nova experiments and target design that allows us to shock compress Cu foils to 3 Mbar, while maintaining a solid state. We present details of the x-ray drive characterization, and results of the instability growth measurements of the shock compressed foils. Comparison with modeling shows that the measured growth is delayed relative to simulation, even when material strength is included in the simulation. This may be the result of a strain-rate dependence for the yield strength. [2] This is approximated in the numerical simulations by scaling the yield strength in the standard Steinberg-Guinan [3] model.

2. Experimental details

We create an x-ray drive inside a cylindrical gold hohlraum using eight beams of the Nova laser. The beams are focused onto the inner wall of the hohlraum through laser entrance holes.

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as shown in Fig. 1a. The foil package consists of a brominated plastic ablator and a Cu foil payload mounted over a hole in the side of the hohlraum. The plastic ablator is 22 µm thick CH with 3% atomic fraction bromine dopant. The payload foil is 15 µm thick. The x-ray drive ablates the brominated plastic, launching a sequence of shocks into the metal foil, compressing and accelerating it away from the hohlraum.

**Figure 1.** a) Schematic showing the internally shielded hohlraum and target geometry for x-ray backlighting. Face-on radiography is done with the backlighter as shown, side-on radiography is done with the backlighter placed behind the target in this view. b) Sample face-on x-ray radiographs shown as modulation in optical depth.

We diagnose the growth of the unstable embedded interface by x-ray radiography using a large area (0.7 mm) backlighter generated with two additional Nova beams aligned to a separate backlighter foil. [4] A 2-3 ns square laser pulse shape was used for these beams, and they were delayed up to 12 ns to record a time-sequence of radiographs over several Nova shots. X-ray pinhole images such as those shown in Fig. 1b were recorded with a gated x-ray framing camera. [5]

In order to shock compress the Cu foil to a peak pressure of about 3 Mbar, while maintaining it in the solid state, we use a high contrast shaped laser pulse and an internally shielded hohlraum. The laser pulse shape is designed to generate an x-ray drive temperature that launches a sequence of staged shocks into the package. The 0.51 µm laser pulse starts with a low intensity foot that delivers 0.4 TW (total for 8 beams) for 2 ns, before ramping up to a peak power of 10 TW. The overall pulse length is 6.5 ns, and the total energy delivered into the hohlraum is about 22 kJ at 0.53 µm laser wavelength. The high contrast pulse shape is shown in Fig. 2a, overlaid with the measured x-ray drive temperature, which is described in the next section below.

The “scale-2” hohlraum is 3.44 mm in diameter, and 5.75 mm long, shown in Fig. 1a. The laser entrance holes are 1.2 mm in diameter, and the holes in the internal shields are 1.6 mm in diameter. The laser beams generate an x-ray radiation environment in the two laser heated cavities of the target. Re-emitted x-rays heat that pass through the holes in the internal shields heat the central (x-ray heated) cavity and launch a sequence of shocks into the package. The internal shields are positioned so that the Au M-band x-ray emission from the laser spots inside
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Figure 2. Laser pulse shape and x-ray drive temperature measurements for a) the low isentrope drive, and b) the square pulse drive. The open circles show measurements of x-ray drive using the absolute sensitivity of individual Dante diodes.

the laser heated cavities do not preheat the package. Without the internal shielding, the 2-4 keV Au M-band emission from the laser plasmas would be absorbed by the full volume of the package, potentially causing the foil to melt and decompress. With the internal shielding, the x-rays incident on the ablator are generated by re-emission from the regions of the wall that are not directly illuminated by the laser beams. The spectrum of these x-rays is nearly Planckian without a significant M-band component.

For comparison, we also shock compress a Cu sample to ~4 Mbar with a single shock. This is well above the 2.2 Mbar Hugoniot melt point for Cu [6] implying that the Cu melts promptly. Here, we use a “scale-3” hohlraum that is 4.8 mm in diameter and 8.0 mm long without internal shielding. A 5 ns square laser pulse (Fig. 2b) is used at a power of ~4 TW at 0.35 μm laser wavelength. The x-ray drive from this target is also shown on the figure. [7]

3. X-ray drive measurement

The x-ray drive inside the hohlraum was measured with the Dante [8] diagnostic, a filtered array of absolutely calibrated x-ray diodes that view the inner wall of the hohlraum through a beryllium-lined diagnostic hole. For the case of the high contrast shaped laser pulse, the lowest energy channels of the Dante (sensitive to ~50 eV photons) detected signals starting at about 1.0 ns. The absolute signal levels from 1-2 diodes were best fit to a Planckian spectrum, which started at about 15 eV and rose to 40 eV at 3 ns. Above 40 eV, enough channels recorded signals that a spectral unfold could be performed, relaxing the Planckian shape requirement. The radiation temperature rose from 40 eV at 3 ns to 90 eV at the end of the laser pulse at 6.5 ns.

For the case of the large hohlraum using a square laser pulse shape, the Dante measurement showed an x-ray drive temperature starting at about 60 eV, ramping up to about 100 eV at the end of the 5 ns laser pulse.

The measured drive temperature for each target is shown overlaid with the laser pulse shapes in Fig. 2. Note that this measured drive is the re-emission from the wall of the hohlraum. The package experiences the x-ray drive that is incident on the wall, which is related to the measured drive by the albedo of the wall. [9] We calculated the albedo correction using the
LASNEX [10] computer code. We assume that the drive temperature ramps up linearly from zero to 15 eV at 1 ns, and we impose a lower limit of 0.1 for the albedo at early time.

We used 1-D LASNEX to model to the Cu as a function of time. Comparing the temperature at the embedded interface with the melt temperature calculated by the Lindemann law [3] (Fig. 3a) suggests that foil remains solid throughout the experiment with the low isentrope drive. The drive launches a sequence of shocks into the foil that start at about 0.4 Mbar, ramp up and peak at 3 Mbar. The peak material temperature from the simulations is about 0.2 eV, compared to the predicted melt temperature of ~0.5 eV.

![Figure 3](image)

Figure 3. Temperature of the Cu at the embedded interface as a function of time for a) the low isentrope drive, and b) the square pulse drive. The Lindemann law melt curves are also shown.

The temperature at the interface late in time is sensitive to the strength of the first shock. This in turn is sensitive to the actual foot temperature in the hohlraum. If the foot temperature is too low, then the second shock may overtake the first shock before it reaches the ablator/Cu interface, and the foil is shocked to a higher adiabat, which means it may melt at late time when the material temperature crosses the Lindemann melt curve.

We measured the trajectory of different thickness foils by using a side-on radiography technique in order to verify the foot and peak drive that is incident on the package in this experiment. We mounted a nominal package consisting of 22 μm ablator with a 13 μm Cu foil on the side of the hohlraum, and used a high magnification x-ray streaked imager to resolve the motion of the rear surface of the foil to characterize the peak drive. We repeated this with a 10 μm brominated plastic ablator with a 3 μm (+1) Cu foil to study the drive in the foot of the laser pulse.

The initial breakout from the thin package is sensitive to the foot drive temperature, and the overall foil acceleration is sensitive to the peak drive. The trajectories for both thick and thin targets are shown in Fig. 4, overlaid with simulations. We reduced the albedo corrected drive in the peak by 7% to match the overall foil trajectory (Fig. 4a). This may indicate uncertainties in the opacities of the plastic ablator at such a low drive temperature, which affects the overall acceleration of the foil. The combination of the measurements with different foil thicknesses constrains the drive.

For the case of the square laser pulse, the x-ray drive shocks the copper foil above the single shock melt pressure of 2.2 Mbar. This melts the foil at the interface, wherein the interface
evolves as a fluid. The simulated material temperature is $>1$ eV, at a pressure of about 4 Mbar, as shown in Fig. 3b.

4. Instability growth experiments

Sinusoidal modulations were machined in the Cu foils with amplitudes of 1.0-2.5 $\mu$m, and wavelengths of 20-50 $\mu$m. We pressed 22 $\mu$m of CH(Br) ablator onto the modulated foils, and then mounted them onto the side of the hohlraum. We used x-ray radiography to measure the mass modulation as a function of time with an Fe backlighter foil, which provided images of optical depth contrast to the 6.7 keV backlighter x-rays. We recorded backlit images such as those shown earlier in Fig. 1b.

Fourier analysis was used to extract the modulation amplitude at each time. We measured the initial Cu foil contrast on a separate Nova shot at the backlighter energy of 6.7 keV. The Fourier amplitude of the 50 $\mu$m wavelength modulation normalized to the initial contrast is plotted in Fig. 5a for the cases of Cu with the shaped low isentrope drive, and in Fig. 5b for the case of the single strong shock using a square laser pulse.

Overlaid on Fig. 5a, we have plotted the growth of the instability due to the low isentrope shaped drive modeled for the 50 $\mu$m wavelength in three different ways: using a fluid model (LASNEX with no material strength included) including a material strength package in LASNEX as described by Steinberg et al, and by artificially enhancing the material yield strength by a factor of 30. The fluid simulations done for the 5 ns square laser drive are shown in Fig. 5b.

When Cu is shock compressed by the low isentrope drive, the instability growth is reduced relative to the fluid calculation. In contrast, the instability growth (with no material strength included) is in agreement with the fluid modeling when the sample is compressed with a single strong shock.

Incorporating the material strength model described by Steinberg et al into the LASNEX simulations results in an instability growth history that is not very different than the fluid case. Enhancing the yield strength by 30 x, however, leads to a reduced growth, in better agreement with the data. Note that artificially scaling the yield strength in this way may be a crude approximation to a strain-rate dependence of the yield strength. [2]