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Los Alamos
NATIONAL LABORATORY

DYNAMIC PROPERTIES OF SHOCK LOADED THIN URANIUM FOILS *

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Abstract. A series of spall experiments has been completed with thin depleted uranium targets, nominally 0.1 mm thick. The first set of uranium spall targets was cut and ground to final thickness from electro-refined, high-purity, cast uranium. The second set was rolled to final thickness from low purity uranium. The impactors for these experiments were laser-launched 0.05-mm thick copper flyers, 3 mm in diameter. Laser energies were varied to yield a range of flyer impact velocities. This resulted in varying degrees of damage to the uranium spall targets, from deformation to complete spall or separation at the higher velocities. Dynamic measurements of the uranium target free surface velocities were obtained with dual velocity interferometers. Uranium targets were recovered and sectioned after testing. Free surface velocity profiles were similar for the two types of uranium, but spall strengths (estimated from the magnitude of the pull-back signal) are higher for the high-purity cast uranium. Velocity profiles and microstructural evidence of spall from the sectioned uranium targets are presented.

INTRODUCTION

Previous shock compression studies of depleted uranium have investigated the effect of impurity and strain rate upon spall strength.[1-4] An increase in spall strength has been observed for depleted uranium with increasing strain rate. Higher spall strength has also been reported for alloyed uranium as compared to pure uranium.[2]

In the present work we report the results of spall experiments completed on two different depleted uranium materials. For the first set high purity (electro-refined) uranium was used to generate baseline spall strength data. The second set of spall experiments was conducted on rolled uranium foil having a relatively high number of inclusions. In these uranium experiments we varied the impactor velocity by adjusting the driving laser pulse energy. This allowed us to achieve a range of input pressures and tensions, making it possible to monitor the spall process, via the uranium's free surface velocity, from pre-spall to incipient spall and finally to complete separation.

An especially interesting aspect of the present spall experiments on the electro-refined uranium is that the ratio of the grain size to the sample thickness is approximately unity. These experiments, as well as those planned, will help resolve questions which arise when shock-wave experiments are scaled to sub-millimeter dimensions.

EXPERIMENTAL

In this study, shock waves are generated in uranium targets by impacting them with copper flyers. The copper flyers are accelerated by an Nd:Glass single-shot laser with a pulse duration of 20 ns FWHM. Conversion of the laser pulse to kinetic energy of the flyer is accomplished by focusing the laser beam onto an area of vapor

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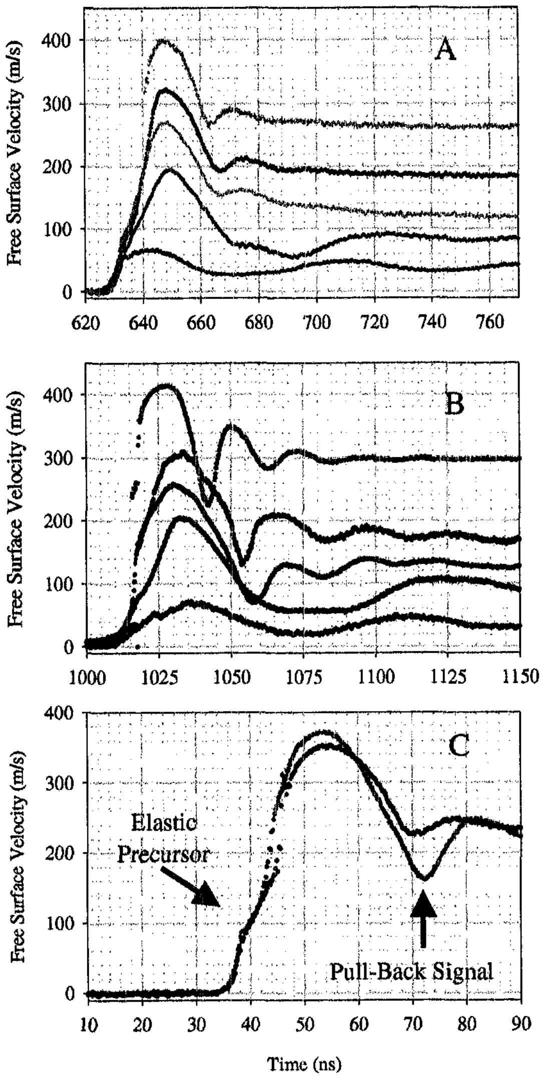

FIGURE 1 Selected free surface velocity profiles for A) rolled uranium foil and B) electro-refined (high-purity) cast uranium. C) Comparison of electro-refined (higher peak and greater pull-back) and rolled uranium foil velocity profiles. Pull-back signals in both velocity profiles indicate spall has occurred; their magnitude is proportional to the spall strength.

deposited materials sandwiched between the copper flyer and a transparent window (BK-7)[5]. The windows are coated at Los Alamos by vapor deposition. Flyers are laser-cut or punched to 3 mm diameter circles from 0.05-mm thick OFHC copper purchased from Goodfellow Corp. Uranium foil, rolled to 0.1 mm at Los Alamos in the early 60's, and electro-refined cast uranium was used for the targets in these tests. The rolled uranium foil samples were briefly electro-polished to remove the oxide layer and measured for thickness before loading in the sample holders. The electro-refined uranium foils were cut from cast stock with a low-speed diamond saw and ground/polished to a final thickness of approximately 0.1-mm. Metallographic analysis of the rolled uranium foil revealed a high concentration of inclusions, which were elongated by the rolling process along planes parallel to the foil sheet. However, we presently do not have a quantitative description of the uranium foil's purity.

Time-resolved motion of the uranium free surface was measured with a velocity interferometry system or VISAR (Velocity Interferometer System for Any Reflector). Dual VISARs were used to avoid ambiguity in the addition of missing fringes. The diagnostic laser (532 nm) used for these measurements was focused to a spot size less than 100 μm.

RESULTS & DISCUSSION

Ten spall experiments were completed on the 0.1-mm rolled depleted uranium foils and nine experiments were completed on the electro-refined uranium samples. The uranium's peak free surface velocity for both series ranged from 0.07 to 0.4 km/s, corresponding to a maximum compressive pressure range of 16 to 105 kbar.

Free surface velocity profiles for several of these experiments are shown in Figure 1. Wave profiles from both types of uranium exhibit an initial velocity jump of 80 to 100 m/s, believed to be an elastic precursor (Figure 1C). This is approximately twice the elastic limit measured on thick (many millimeters) uranium targets using gas guns.[1-4] A slower velocity increase following the elastic precursor is then observed prior to arrival of the plastic wave. Arrival of the plastic wave, the fastest part of the velocity jump, frequently exceeded the temporal resolution of the velocity interferometers and fringes were lost for many of these experiments.

An experiment was completed for each alloy where the peak uranium free surface velocity was below the elastic limit (lowest velocity profiles in Figure 1A & 1B). The velocity profiles for these experiments show smooth waves with a frequency corresponding to a wave oscillating in the target (original thickness) at the longitudinal sound speed (C_L= 3.451 km/s).[3]

Wave profiles for those spall experiments where the uranium's peak free surface velocity was the highest show an abrupt change in velocity after the initial decrease in the free-surface velocity (Figure 1C). This pull-back occurs in advance of the smooth velocity increase associated with the oscillating wave described for the lowest velocity experiments and is associated with spall in the uranium target. Additional evidence that spall has occurred comes from the post-pull-back ring frequency, which is too fast for oscillations in the sample's original thickness.

Velocity profiles for experiments falling between those clearly exhibiting spall and those having only a smooth oscillating wave have subtle changes in the slope of the velocity profile. These irregularities occur near the time that pull-backs are observed for the higher pressure shots and appear to be the first indication of incipient spall measurable with a single point velocity interferometer.

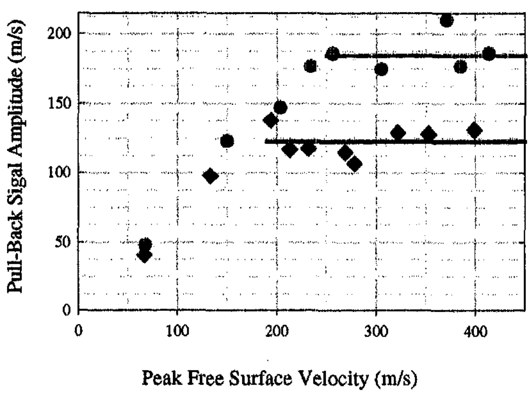

FIGURE 2 Pull-back results from spall experiments on rolled (diamonds) and electro-refined (circles) uranium. Results from both samples show a linear increase in pull back amplitude with increasing pressure, but the electro-refined plateaus at a higher level (185 m/s) than the rolled uranium foil (123 m/s).

A plot of the peak free-surface velocity versus the amplitude of the pull-back signal, which is proportional to the spall strength, is shown in Figure 2. This plot shows a clear difference between the electro-refined and rolled uranium samples with respect to the amplitude of the pull-back. The data for both plots follow a straight line with positive slope beginning at the origin. The pull-back velocity remains constant at roughly 120 m/s above a peak free-surface velocity of about 190 m/s for the rolled uranium foil. However, for the electro-refined material the pull-back velocity continues to rise to about 185 m/s and then remains constant above a peak free-surface velocity of approximately 250 m/s. The average pull-back for experiments in this constant region is 123 m/s and 185 m/s for the rolled and electro-refined uranium, respectively.

An analytical method based on the pull-back amplitude or difference between the peak velocity, U_{max}, and the first minimum, U_{min}, in the free surface velocity profiles can be used to estimate the tensile spall strength.[6]

$$P_{spall} = 0.5\, Z\, (U_{max} - U_{min}) \qquad (1)$$

Using pull-back values of 185 and 123 m/s in Equation 1, where Z is the product of the initial density (18.96 g/cm^3) and wave speed (2.49 km/s), we obtain spall strengths of 44 kbar and 29 kbar for the electro-refined and rolled uranium, respectively.

The electro-refined uranium shots show a decrease in the time between the initial velocity jump and the pull-back signal with increasing pressure. This phenomenon is not clearly seen in the rolled uranium data, if present at all. Wave profiles from both types of uranium show an increase in the slope of the pull-back signal with increasing pressure.

Strain rates, ($\dot{\varepsilon}$), for the three highest-pressure shots for both materials are calculated from the slopes, (du/dt), of the pull-back signals, i.e. the linear portion of the velocity time profile between the peak free surface velocity and the pull-back minimum. Slopes for these shots from linear fits are –11 m/s/ns and –20 m/s/ns for the rolled and electro-refined uranium respectively. Strain rates are calculated using the following relationship[7]

$$\dot{\varepsilon} = -\, du/dt \,/\, 2\, C_0, \qquad (2)$$

where C_0 is taken to be 2.49 km/s. Strain rates calculated with these slopes using Equation 2 are 2 x 10^6 s^{-1} for the rolled uranium and 4 x 10^6 s^{-1} for the electro-refined uranium.

Metallographic cross-sections of the three spall experiments with peak velocities above 300 m/s are shown in Figures 3 and 4. Complete separation, (spall) is clearly shown in each of these uranium samples. Higher magnification indicates the spall to be primarily brittle, which is consistent with prior work by Zurek[8] et al.

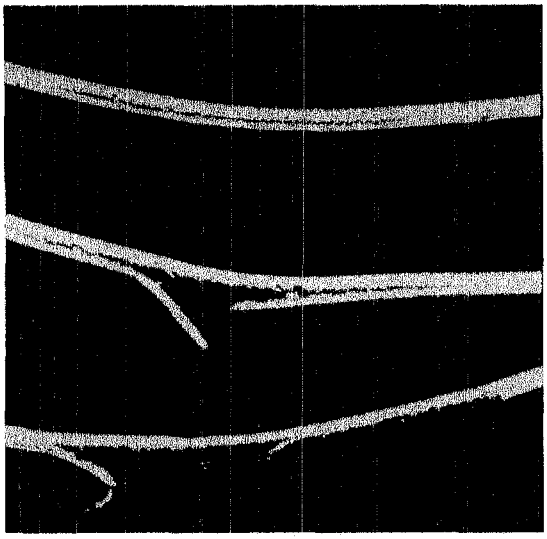

FIGURE 3 Post-shot metallography photographs of rolled uranium foil spall shots with peak free surface velocities, 322, 353, and 399 m/s, from top to bottom.

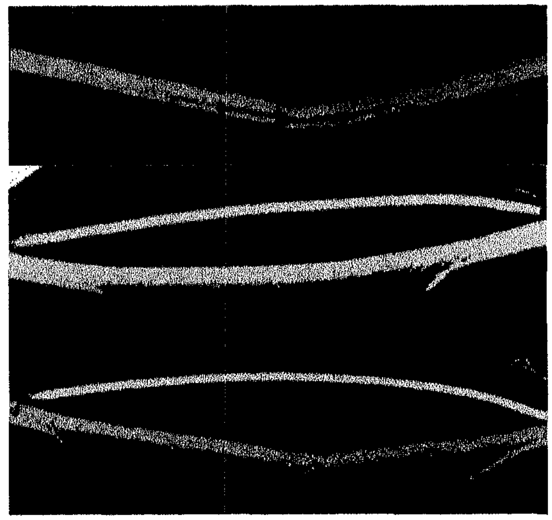

FIGURE 4 Post-shot metallography photographs of electro-refined (high-purity) uranium spall shots with peak free surface velocities, 371, 385, 413 m/s, from top to bottom.

CONCLUSIONS

Laser-driven flyer spall experiments on electro-refined (high purity) and rolled uranium foil have been completed. Samples from the electro-refined uranium were cut and ground to final thickness from cast stock, having an average grain size of 0.1 mm, similar to the sample thickness. The rolled uranium had a relatively high number of inclusions, which had been rolled into planes parallel to the copper impactor. For each shot, free-surface velocity profiles were measured. Abrupt pull-back signals or relatively subtle slope changes are correlated with complete or incipient spall, respectively. At higher velocities the average pull-back signal amplitude for the rolled uranium was 123 m/s, while that of the electro-refined uranium was 185 m/s, corresponding to spall strengths of 29 and 43 kbar, respectively. This pull-back amplitude plateau (Figure 2) was reached with uranium peak free surface velocities below 200 m/s for the rolled foil. Higher pressures were required for spall in the electro-refined material, where the plateau in the pull-back amplitude was not reached until peak free surface velocities of around 250 m/s were reached.

Planar inclusions are the most probable reason for the lower spall strength measured for the rolled uranium foil. The relatively large grains in the electro-refined uranium may also contribute to the higher strength, but additional studies will be required before this is confirmed.

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