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Title:

MINIFLYER EXPERIMENTS: SPALL MEASUREMENTS ON URANIUM

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Abstract

A laser-launched miniature flyer system (MiniFlyer) is being used to study the dynamic properties of materials. A 3-mm diameter by 0.05-mm thick flyer plate is accelerated by a laser-pulse-induced plasma contained between a clear window substrate and the flyer plate. The substrate is coated with carbon, aluminum oxide, and aluminum to enhance the plasma formation process. The flyer plate is accelerated to a velocity up to 0.7 km/s and interacts with a target producing a shock pulse. Dynamic measurements of the target free surface particle velocity can be used to provide information on phase transformations, sound speed, elastic-plastic behavior, spall strength, and strain rate. These measurements are made with a VISAR (Velocity Interferometer System for Any Reflector).

In the experiments presented here the flyer impacts a spall target producing a shock pulse which moves through the target, interacts with the free surface producing a backward traveling rarefaction. When this rarefaction interacts with the rarefaction from the flyer plate's free surface, tension is produced in the target material and, if conditions are right, a spall occurs. This kind of experiment has been performed on a number of different materials including uranium, two plutonium alloys, gold, three orientations of single crystal copper, three types of polycrystalline copper, and tantalum. A complete description of these tests is not possible within the constraints of the present report so we focus on one set of uranium experiments. The target material for this work was uranium foil, which was rolled to approximately 0.1 mm thickness at Los Alamos in the early 60's. The free surface particle velocity profiles are given, along with analysis and discussion of our interpretation of these records. Several samples were observed to have spalled as confirmed with post shot metallography. We estimate a spall strength of 30 kbars for this material.

Introduction

The appeal of the MiniFlyer is the potential of generating Hugoniot data, sound speeds, spall strength and phase transformation data for small samples as a function of temperature for a variety of materials of importance to the nuclear weapons stockpile. Two unique aspects of the MiniFlyer are the high sampling throughput and very small sample sizes used for the experiments. Especially appealing is the potential of testing material taken directly from pits of various ages; many of these aging effects are lost by recasting or other processes required to prepare samples for testing by traditional techniques.

The principal objective of the MiniFlyer project is to measure dynamic properties of plutonium and uranium materials taken directly from pits. Such information would be used to construct a matrix of dynamic properties verses material and age. However, experiments on plutonium have only recently been restarted due to the security stand-down early in 1999 and a limited number of plutonium experiments have been completed to date. Consequently, the focus of this report is a set of experiments completed on very old uranium foil rolled in the early ‘60s at the Sigma complex within the Los Alamos National Laboratory. The ten uranium experiments reported here represent a small portion of the work completed over the past year, since a technical description of the spall studies of all the materials we have studied would be too extensive for this report. Some Pu experiments have been completed but analysis of them is not yet complete; these will be reported later. Reports and papers are in process describing some of the other work, such as single-crystal and polycrystalline copper experiments.

A secondary objective is to upgrade and understand the driving technique, existing instrumentation, and the shock processes involved in the MiniFlyer technique. We are addressing this in several ways: 1) generation of MiniFlyer data on materials where traditional gun data exist for comparison; 2) improvement of our driving laser to achieve a greater range of shock pressures; 3) development of diagnostic tools to measure flyer/target planarity and tilt; 4) design and implementation of a temperature control capability to study dynamic properties as a function of temperature. These efforts are being addressed simultaneously with the experiments being done.

Experimental Approach

In this study shock waves in the uranium target are generated by impacting uranium foils 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 beam onto an area of vapor deposited materials sandwiched between the copper flyer and a transparent window (BK-7). Additional details of this system are described in a recent paper. [1]

Flyers are laser cut 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, is used for the targets in these tests. The samples were briefly electro-polished to remove the oxide layer and measured for thickness before loading in the sample holders. Final thickness ranged from 0.088 to 0.101 mm. Metallographic analysis of this material revealed a high concentration of inclusions, which were elongated by the rolling process. 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 laser 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 CW with a power of about 200 mW) used for these measurements was focused to a spot size less than 100 μm.

The electro-polished uranium surface provided a dull or matte finish, a good diffuse reflector for the VISAR measurements. The ten uranium samples were prepared at the same time, but five were fired within a few hours of preparation and the remaining five the next morning. Significant degradation in the VISAR's signal-to-noise ratio was observed for these, presumably due to oxidation overnight.

Results & Discussion

The free surface velocity profiles from the 10 uranium spall experiments are shown in Figure 1. For convenience, these experiments are identified in this text by their peak velocities, e.g. u_{peak} 67, u_{peak} 399, etc. Qualitatively, the profile features are similar to previous uranium spall (gas gun) experiments by Hixson et al. [2] and Grady [3] but time scales are greatly reduced (from 1500 to 40 ns). Their experiments were done on gas guns and the samples were 4 to 8 mm thick. Each profile (except the two of lowest velocity) exhibits an initial rise to a velocity of about 80 m/s. This shoulder is similar to that observed in the earlier work and described by Grady as an elastic precursor wave. This first wave plateaus at approximately 40 m/s or 1.5 GPa in Grady's work. The value for this plateau in the current work is higher, 80 m/s, indicating that the precursor decay has not been completed in these thin samples or that the samples of uranium were not equivalent. In order to study the elastic precursor development, experiments with a window that impedance matches the uranium (such as sapphire) and different uranium thicknesses would be required. These experiments are planned for the future.

A relatively slow velocity increase follows this initial elastic precursor in both our experiments and those of Grady. Grady attributes this to strain hardening prior to arrival of the plastic wave. A sharp velocity increase is then observed; this is the plastic wave interacting with the free surface. Several of the VISAR records "lost fringes" in this wave, indicating the plastic shock front jump exceeded the resolution of our diagnostic instrumentation (which is less than 2 ns).

The lowest velocity wave profiles, u_{peak} 67 and u_{peak} 133, appear to be the result of the flyer exciting an elastic wave rather than a shock wave. The late time oscillations (not shown in Fig. 1) have a period corresponding to a wave velocity within 5% of the elastic sound speed, (C_L = 3.451 km/s). These two curves are distinct from the remaining 8 profiles in that there is no “bump” after the rapid decline (following the velocity maximum). This bump is thought to be characteristic or indicative that spall is occurring or trying to occur. This feature is very distinct for the three higher pressure profiles with peak velocities above 300 m/s. It is much less distinct for u_{peak} 194; u_{peak} 194 is the lowest velocity profile to have this feature. This profile also shows late time amplitude oscillations consistent with an elastic sound wave traveling through the uranium’s original thickness, an indication of no spall.

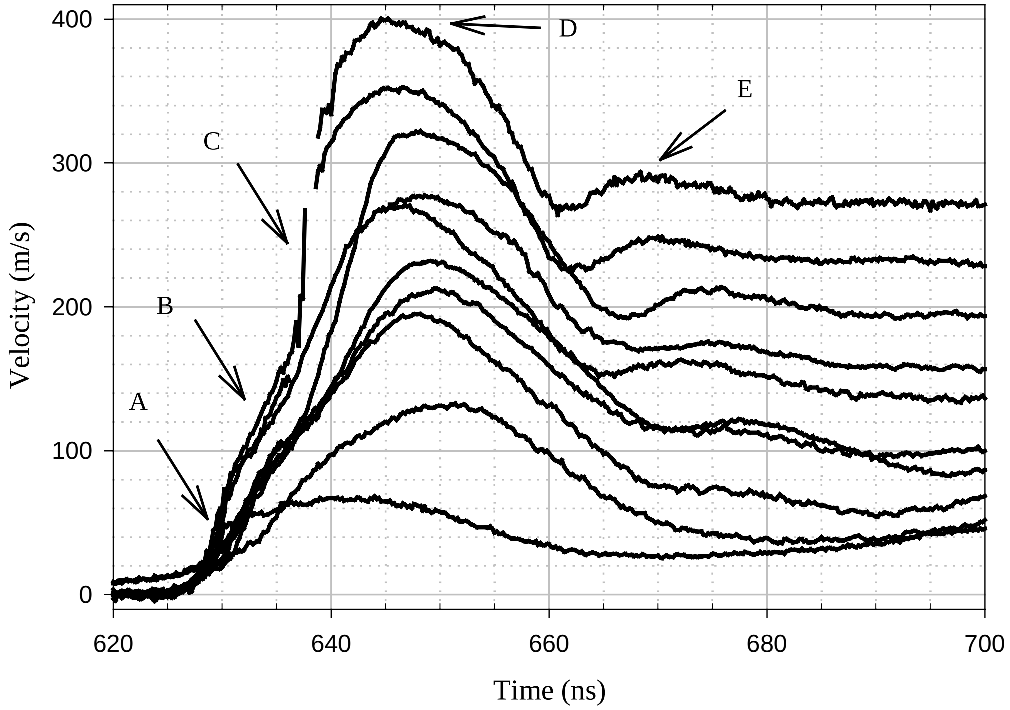

Figure 1: Velocity time profiles for depleted uranium foil spall experiments. Profiles exhibit an initial jump in velocity due to arrival of the elastic precursor (A). This is followed by a region of relatively slow acceleration (B) associated with strain hardening. The region of highest acceleration (C) marks the arrival of the plastic wave. Peak velocities achieved for each shot (D) are used to identify shots in the text. The “bump” in all but the two lowest velocity waveforms (E) is associated with spall.

Metallographic cross-sections of the three spall experiments with peak velocities above 300 m/s are shown in Figure 2. Complete separation, (spall) is clearly shown in each of these uranium samples at the expected location based on the properties and thickness of the copper flyer and uranium target. Post-shot metallographic pictures for u_{peak} 399 show a completely detached spall layer. An average of several measurements of the photographs yields a spall layer thickness of 0.042 mm for this sample. Metallographic photographs of u_{peak} 353 show similar, but less extensive, damage. The last shot for which we have both dynamic and post-shot confirmation of spall is u_{peak} 322. The velocity profile for this shot is very similar to the previous two, but the spall was not obvious before cross-sectioning. Higher magnification indicates the spall to be primarily brittle, which is consistent with prior work by Zurek et al.[4] Cross-sections of the other experiments are not yet fully analyzed.

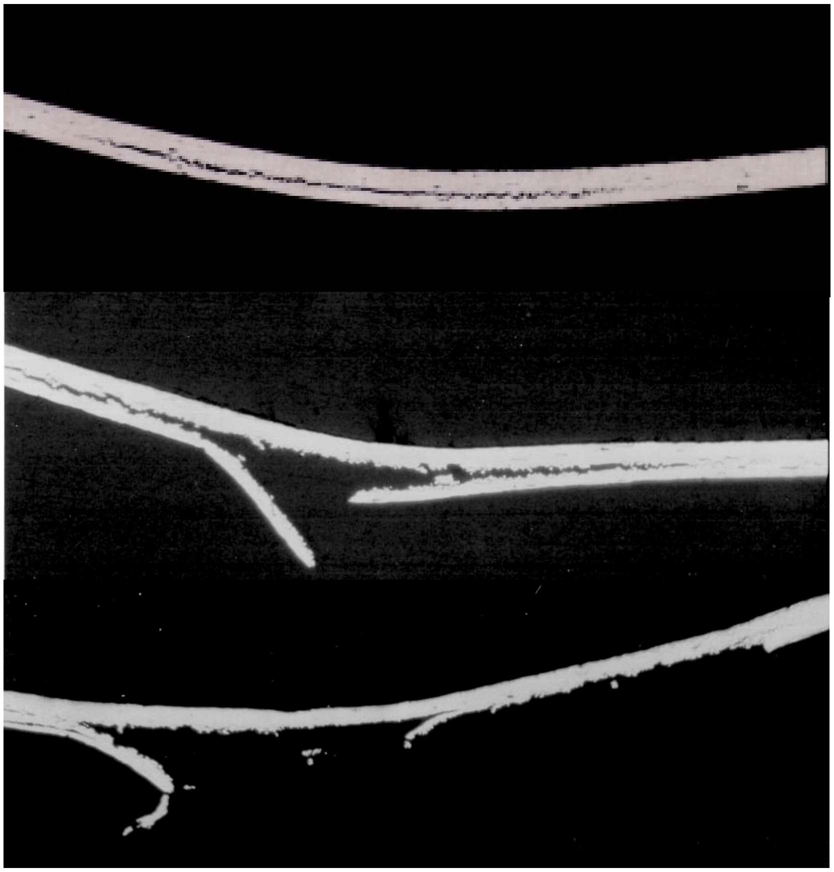

Figure 2: Post shot metallography photographs of spall shots u_{peak} 322 (top), u_{peak} 353 (middle), u_{peak} 399 (bottom).

Strain rates, ($\dot{\varepsilon}$), for the three highest-pressure shots 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. The slopes for these three shots are given in Table 1. Linear fits to this data yield slopes ranging from –11.8 m/s/ns for the u_{peak} 399 velocity profile to –10.1 m/s/ns for the u_{peak} 322 velocity profile. We calculated strain rates using the following relationship [5]

$$\dot{\varepsilon} = - du/dt \,/\, 2\, C_0 \qquad (1)$$

where C_0 is taken to be 2.49 km/s [3]. Strain rates calculated with these slopes using Equation 1 range from 2.4 x 10^6 $s^{-1}$for the highest-pressure shot, u_{peak} 399, to 2.0 x 10^6 s^{-1}, for the lowest, u_{peak} 322.

By using the Figures in Grady's and Hixson et al. papers, along with Equation 1, we estimate strain rates for their experiments to be about 4 x 10^5 s^{-1}. This gives us a method for direct comparison of the strain rates in each of these studies. Uranium target thickness in this work was approximately 0.1 mm. Targets for the referenced gun work ranged from 4 to 8 mm; consequently, the MiniFlyer experiments are expected to have higher strain rates than the gun experiments. Based on the above estimates, our strain rates are five times higher than those of the previous works.

Shot u_{peak} (m/s)	Sample Thickness	$\Delta u_{pullback}$ (m/s)	P_{spall} (kbar)	*du/dt* m/s/ns	$\acute{\varepsilon}$ (s^{-1})	Spall Thickness (mm)
67	0.101					
133	0.100					
194	0.101	125				
213	0.088	117				
232	0.099	118				
269	0.089	115				
278	0.098	107				
322	0.100	129	30.4	-10.1	2.03E6	0.040
353	0.090	128	30.2	-11.1	2.24E6	0.034
399	0.097	131	30.9	-11.8	2.37E6	0.042

Table 1: Experimental results for uranium spall experiments. Individual shots are identified with their peak free surface velocities.

The difference between the peak free surface and subsequent pullback minimum velocities, $\Delta u_{pullback}$, is directly related to the spall strength of the material, (P_{spall}). Hixson reported spall results for two uranium samples of different purity and reported equivalent spall strengths, but noted differences in the waveform shape. Pullback amplitudes from Hixson et al. are approximately 65 m/s and they reported spall strengths of 15 to 19 kbars. Grady's work, which does not give the purity of the uranium tested, reports pullback amplitudes ranging from 80 to 102 m/s and spall strengths from 27 to 33 kbars. A trend towards higher spall strength with increasing impact stress is indicated in these two studies. The three spall profiles discussed in the present work had higher peak free surface velocities, 322, 353 and 399 m/s. The corresponding pullback amplitudes were 129, 128, and 131 m/s. Pullback amplitudes of the lower pressure shots in this work range from 107 to 125 m/s. The analytical form shown in Equation 2 [6],

$$P_{spall} = 0.5\ Z\ (U_{max} - U_{min}), \qquad (2)$$

was used to determine spall strengths (P_{spall}) where the impedance, Z, is the product of the density (18.94 g/cm^3) and the bulk sound speed (2.49 km/s). Using this relationship we calculate spall strengths of about 30 kbars (Table 1).

Conclusions

Uranium velocity profiles in the present and two previous works referenced here have several common features: 1) an elastic precursor wave, 2) a relatively slow velocity rise attributed to strain hardening, 3) a fast velocity increase associated with the plastic shock front, and 4) a pullback signal characteristic of spall. Strain rates for these MiniFlyer experiments are measured to be 2 x 10^6 s^{-1}, which are approximately 5 times higher than those of the two previous studies. We report spall strengths of 30 kbars for the uranium foil tested. Cross sections of three shots, having peak free surface velocities greater than

300 m/s, corroborate our conclusion that each spalled. Work is continuing in this area and future experiments are planned on uranium and uranium-niobium alloys.

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