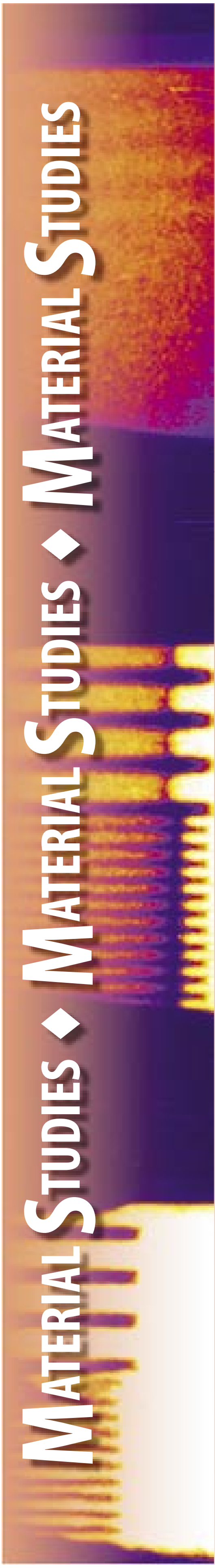

High-Strain-Rate Experiments to Determine the Dynamic Yield Strength of Copper

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A series of experiments, known as the Russian High Strain Rate (RHSR) experiments, has been designed and partially completed to determine the dynamic yield strength of copper. The data obtained from this experimental series are used to validate theoretical and computational models of material behavior at high strains (100%–150%) and strain rates (~ 10^6/s).[1] To achieve these high strains and strain rates, a two-stage explosively driven pulsed-power generator is used to produce high currents that magnetically implode a cylindrical aluminum liner onto a copper sample. The sample, also cylindrical, incorporates machined sinusoidal perturbations of two different wavelengths on its outer surface. Theoretical models predict that the growth rate of these perturbations is wavelength dependent and directly related to the dynamic yield strength of the copper.

The RHSR experiments are important to refine and validate computational models of dynamic material strength under high-strain and strain-rate conditions. Validation of such models is an essential element of the ASCI-code-development effort that will support nuclear-weapons certification in the future. Additionally, these experiments have the added benefit of fulfilling a goal of the National Nuclear Security Administration (NNSA) to significantly increase collaboration between Russian and U.S. weapons laboratories on fundamental science issues.

Experimental Design

Because the Atlas pulsed-power capacitor bank is presently being relocated from LANL to the NTS, the high currents needed to perform this type of experiment are currently not easily attainable in the U.S.[2] However, the VNIIEF scientific research institute in Sarov, Russia, has developed an explosively driven pulsed-power generator that can supply the required 35-MA current.[3] The VNIIEF device consists of two parts: a helical explosive magnetic generator (HEMG) and a multi-element disk explosive magnetic generator (DEMG) (Figure 1). Both devices use rapid magnetic flux compression to generate a very high, short pulse of electrical current. The basic concept behind these devices is that a small "seed" current creates magnetic flux through a volume within the generator. Igniting high explosives rapidly collapses this volume, and because the flux is initially preserved, a portion of the work done by the high explosive is converted to electrical current. In the case of the RHSR device, the HEMG delivers 6.5 MA as the "seed" current for the DEMG that in turn delivers ~ 35 MA through a liner inside the physics package.

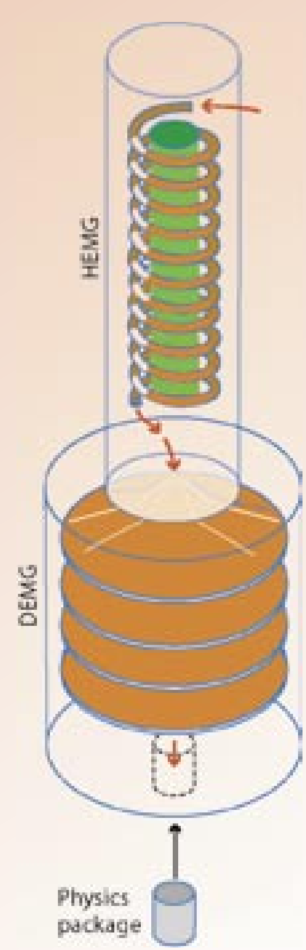

Figure 1. The combination of the HEMG and DEMG deliver a peak current of ~ 35 MA through the liner in the physics package.

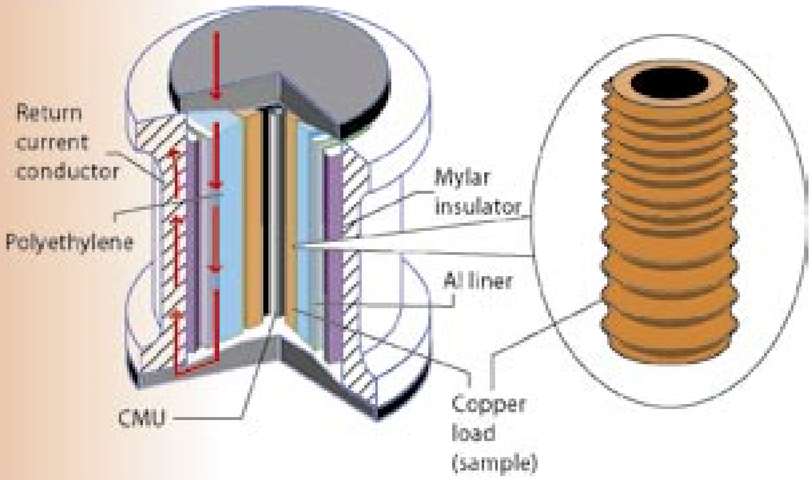

Figure 2. The cylindrically symmetric physics package contains a copper sample that is imploded by the aluminum liner.

The liner is an aluminum cylinder with a 4-mm-thick wall and an inner diameter of 96 mm. The current flowing through it causes the liner to magnetically implode and push on polyethylene that fills the entire space between the liner and a 52.6-mm-diam copper sample (Figure 2). The copper sample has 2.0- and 4.0-mm-wavelength sinusoidal perturbations machined on its exterior surface with initial amplitudes of 1.0 mm. The volume inside the cylindrical copper sample is evacuated and contains a stainless-steel central measuring unit (CMU).

During the implosion, the polyethylene shocklessly transfers the pressure from the liner to the copper cylinder causing it to radially compress to a peak pressure of 160 kbar at a strain rate of ~ 9×10^5/s. Under these conditions, the copper-polyethylene interface is Rayleigh-Taylor unstable, and the perturbations will grow as a function of time during the implosion.[4,5] The design of the RHSR experiments assumes that the dynamic yield strength of polyethylene is small enough that it can be neglected, and as a result, its hydrodynamic properties closely approximate those of a fluid. This assumption is important because it allows the dynamic yield strength of the copper to be determined directly from the growth rate of the perturbation amplitude.

Experimental Diagnostics and Data

A Faraday rotation diagnostic is used to measure current delivered from the DEMG to the load as a function of time.[6] The diagnostic consists of a single-mode quartz fiber that encircles the entire electrical current path to the liner. An 830-nm laser diode injects linearly polarized light into the fiber, and current flowing through the load creates a magnetic field that causes the polarization of the light in the fiber to rotate. The light rotation angle is subsequently detected using an optical polarization analyzer once it exits the fiber. The time-dependent current through the load is then calculated using the Verdet constant (2.65 +/- 0.03 rad/MA) of the fiber that relates the light-polarization rotation angle to the enclosed current. Because this measurement technique is only sensitive to current that passes through the area defined by the fiber loop, an accurate measure of the current through the liner can be obtained.

A B-dot is an inductive probe that consists of a center-wound wire loop inserted into current-carrying regions of the load, HEMG, and DEMG. Current flowing in the region of the B-dots generates a time-varying magnetic field that induces a small current in each B-dot loop. This B-dot signal is proportional to the time derivative of the current flowing in the experimental device. Because the B-dot is extremely sensitive to changes in current, it provides critical timing information about the performance of the device, including the start of current flow, peak current time, and copper impact on the CMU.

Thus far, two of the three planned experiments have been performed: RHSR-0 and RHSR-1. The peak current, as measured with the Faraday rotation diagnostic, was 34.9 MA for RHSR-0 and 34.6 MA for RHSR-1 (Figure 3). The B-dot data obtained from the RHSR-0 experiment shows that peak current occurred at 27.1 µs after the high-explosive detonator in the DEMG was initiated.

A VISAR is an interferometer used to measure the velocity of a reflective surface as a function of time.[7,8] The VISAR uses a 532-nm laser coupled to a glass fiber that transports the light to the inside surface of the copper load via the CMU. Light reflected from the copper surface is recollected and transmitted down a separate glass fiber to an interferometer. Upon entering the interferometer, the reflected light is split into two optical paths with different optical lengths and subsequently recombined to interfere with one another. Motion of the copper sample produces a Doppler shift in the recollected light and, as a result, an interference fringe shift that is recorded as a function of time. The velocity of the reflective copper surface is proportional to this fringe shift and was measured to be 3.1 mm/µs at impact with the CMU in both

RHSR-0 and RHSR-1. Additionally, the VISAR data indicated the impacts occurred 32.5 µs after the DEMG detonators were initiated (Figure 4). These data provide information about both the load hydrodynamics as a function of time and the time when the load reaches a radius of 10 mm during the implosion.

Low-energy x-ray radiographs were obtained to measure the perturbation growth of the load at three distinct times during the hydrodynamic explosion. Two different x-ray source designs were used in the experiments: one was designed and built by LANL, and the VNIIEF team provided the other. The LANL x-ray source consists of an x-ray head coupled to a 900-kV Marx bank via ~ 20 m of coaxial cable.[9] The x-ray head contains a 1.5-mm-diameter tungsten anode, which generates a 20-ns-long x-ray pulse. The x-ray spectrum of this pulse is comprised primarily of K_α-line and Bremsstrahlung radiation with an endpoint energy of ~ 350 kV.

Transverse x-ray radiographs of the dynamically evolving copper perturbations are acquired by locating the x-ray heads and films on opposite sides of the load. A steel enclosure protects the film from shrapnel generated by the ~ 175-lb high-explosive charge in the DEMG and the aluminum-return-current conductor. The film is recovered after the experiment to be developed and digitized for later analysis.

The flash x-ray sources were fired to record images from ~ 1.5 µs before impact to ~ 1.5 µs after impact of the copper sample upon the CMU. These radiographic times were chosen to provide images both during the shockless perturbation growth phase of the implosion and to observe the effect of the reflected shock generated upon impact with the CMU. Only the single radiograph produced with the VNIIEF x-ray source was successfully recovered from RHSR-0. Damage to the LANL films by the high explosive and shrapnel prohibited any additional successful data retrieval. Improvements in the film protection systems enabled the successful recovery of all three radiographs from the RHSR-1 experiment, although each piece of film sustained moderate to severe shrapnel damage.

The radiographs from both experiments showed shockless-perturbation-amplitude growth of A/A_0 ~ 2–3 before CMU impact. The amplitude then rapidly dropped to A/A_0 ~ 0.7 once the reflected shock exited the copper sample (Figure 5). Given the assumption that the polyethylene moves and flows like a fluid under these dynamic conditions, the perturbation amplitude exhibited significantly less growth than the A/A_0 ~ 8–12 predicted by the theoretical models. There are two possible explanations for this result: (1) the strength model used in the computations does not adequately describe the dynamic strength properties of copper, or (2) the assumption that the polyethylene was a dynamically strengthless material is invalid.

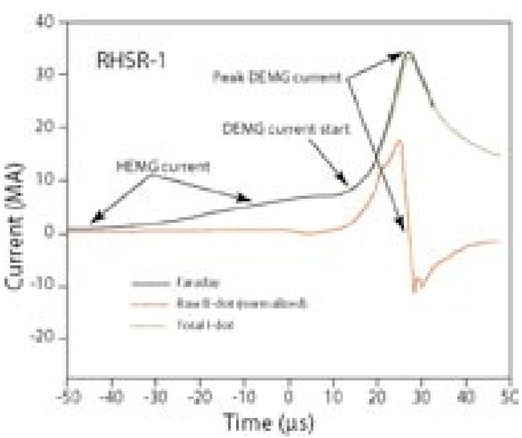

Figure 3. B-dots, proportional to the time derivative of current flowing in the DEMG, indicate peak current occurred at 27.1 µs after detonator initiation. The Faraday rotation diagnostic recorded a peak current of ~ 35 MA.

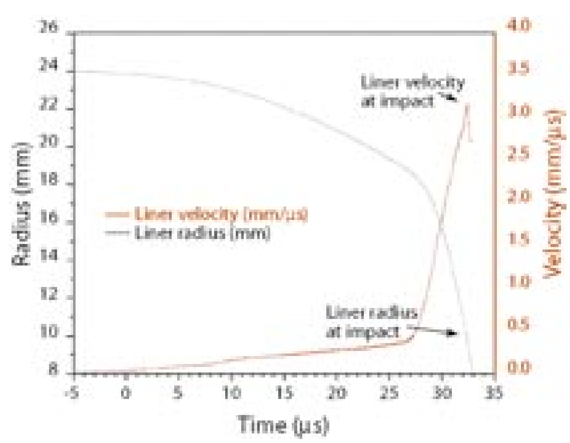

Figure 4. VISAR data indicates the inner surface of the copper is moving 3.1 mm/µs at impact with the CMU.

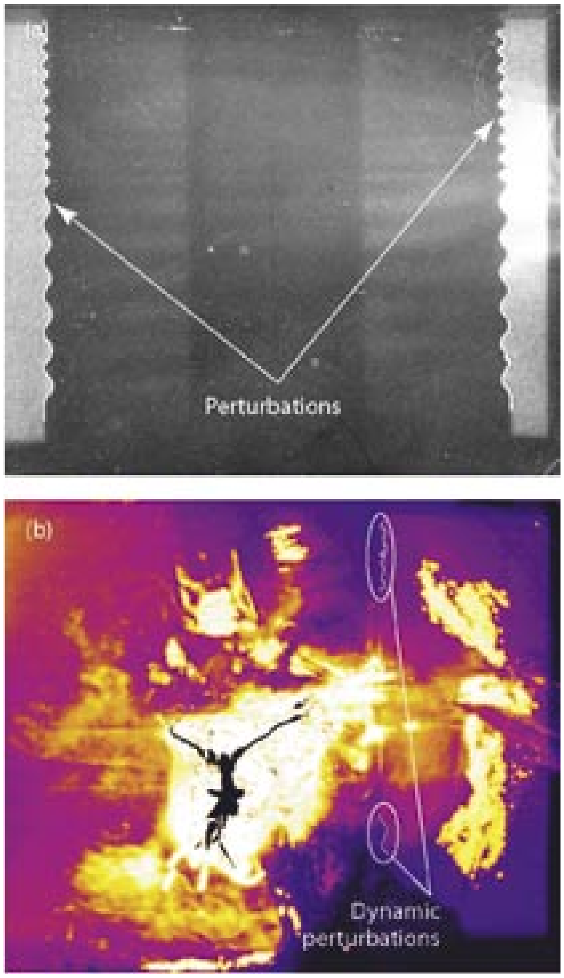

Figure 5. The static (a) and dynamic (b) x-ray radiographs acquired by LANL show the RHSR-1 perturbation edges with the dynamic image quality significantly affected by shrapnel damage. The dynamic radiograph was acquired 1.0 µs after impact of the copper on the CMU.

Conclusion

RHSR-2 is currently being designed using a liquid material (such as butane, water, or ethylene glycol) to eliminate the ambiguity introduced by the polyethylene. However, given this change in materials, a redesign of the load is necessary to maintain the same shockless condition in the fluid that was present using polyethylene in the RHSR-0 and RHSR-1 experiments. The RHSR-2 experiment with its redesigned load is currently scheduled for February 2004.

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