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SHOCK HUGONIOT MEASUREMENTS ON Ta TO 0.78 TPa

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Symmetric impact shock Hugoniot measurements have been made on Ta with an electrically exploded foil gun system. The results obtained to date for the Hugoniot of Ta cover the range 0.19 to 0.78 TPa (impact velocities from 4.0 to 9.7 km/s) and agree with data obtained by other researchers to within 2.7% rms. Recent improvements in the system include electromagnetic shielding of impactor and target, continuous measurement of impactor velocity with a Fabry-Perot interferometer and computer-aided analysis of shot film.

Conservative extrapolation from current operating conditions indicate that pressures of 1.1 to 1.5 TPa could be achieved with little difficulty.

Introduction

To understand and predict the behavior of material at extremely high pressure it is necessary to know its equation of state (EOS) in the appropriate regime. One important aspect of the EOS of any material is its shock Hugoniot, the locus of points in thermodynamic state space which can be reached by a single instantaneous compression, i.e., a shock wave. Knowledge of the shock Hugoniot is especially important in research areas where energy densities and velocities are high such as astrophysics, planetary science studies, meteorite impacts, weapon design, military systems vulnerability and high explosive engineering.

Using the well-known Rankine-Hugoniot relations expressing conservation of mass, momentum and energy across a shock front, a point on the Hugoniot of a material may be completely specified by measuring only two state variables. For instance, if the shock propagation velocity, u_s , and the material velocity behind the shock, u_m , are both measured, then the pressure, compression, density, and specific internal energy in the shocked state are given by:

$$P = P_0 + \rho_0 u_s u_m$$

$$\rho = \rho_0 = \rho_s / (u_s - u_m)$$

$$E = E_0 + 1/2 (P + P_0) (\rho_0^{-1} - \rho^{-1})$$

Many experimental techniques and devices have been devised over the years to measure points on the shock Hugoniot. The classic technique is to accelerate a thin

plate of the sample material into a target of the same material. When the impactor plate collides with the target plate a steady, one-dimensional shock is produced which propagates through the target and back into the impactor. The velocity of propagation of this shock in the target, u_s , is determined by measuring the time of breakout at the front surface of the target on either side of a step, which has been cut into the front surface of the target. The material velocity can be shown by symmetry considerations to be exactly one-half the bulk velocity of the impactor at the instant of impact, i.e., $u_m = 1/2 u_i$, and the impactor velocity can be measured by a variety of techniques. Methods which have been used to accelerate the impactor plate include high explosives in simple and compound systems, single and two-stage gas guns, rail guns, and mass drivers. In the work described in this paper, the impactor is driven by the electrical explosion of a metallic foil in a device which we call an "Electric Gun".¹

Other techniques have been employed which do not directly measure a point on the Hugoniot of the sample material because they measure only one thermodynamic variable, usually the shock velocity, u_s . Useful information can be obtained in such systems through the technique of "impedance matching" provided that another material with known EOS is included in the experiment.²

The LLNL Electric Gun

The highest laboratory pressure achievable in uranium with current two-stage gas guns is about 500 GPa.³ Most metals have equations of state which are relatively simple in this pressure regime. A linear relationship between the shock and material velocities characterizes

the shock Hugoniot, i.e., $u_s = c_0 + su_m$. At extremely high pressures, the equation of state can be accurately calculated from theoretical models based upon the methods of statistical physics.

The region from 0.5 TPa to several TPa is where the largest uncertainties in EOS exist. A promising technology we have developed at LLNL to explore this region is the electric gun.

In an electric gun, an impactor (projectile)—usually a thin foil or a composite of several foils—is accelerated to a high velocity when an adjacent metal foil is electrically exploded by rapid Joule heating (Fig. 1). When the foil explodes, it punches out a section of the impactor and drives it up an evacuated barrel to strike the target.

The energy density achievable in the exploding foil is many times that obtained with chemical high explosives. Moreover, intense magnetic fields generated by the currents flowing in the foil plasma and rear conductor impart a substantial additional acceleration (Lorentz acceleration) to the impactor. As a result, the projectile may be accelerated to velocities well beyond

the reach of other technologies. The fastest electric-gun system in use at LLNL has accelerated plastic projectiles 0.3 mm thick and 8 mm in diameter to a velocity of 30 km/s and composite plastic-Ta projectiles of the same diameter to 12.6 km/s. This capability led us to explore the electric gun's potential as a shock-wave generator in experiments designed to characterize the EOS of a material at high pressures.

Apart from its electrical power source, the electric gun is an inexpensive, throw-away device that dissipates a relatively small amount of energy compared to gas guns or high-explosive systems. Because it is self-contained, it is especially suited to experiments on hazardous materials that might otherwise contaminate an expensive and complex research facility.

Although the electric gun is conceptually simple, a number of difficulties arise in applying it to EOS experiments. A substantial part of our research has been aimed at identifying and solving such problems as hydrodynamic jetting, target preheat and premotion, impactor preheat and nonplanarity. We have also developed experimental and diagnostic techniques with accuracies sufficient to measure impactor velocity and shock transit times to 1 or 2%.

Figure 1. Exploded and partial cutaway view of a typical electric gun EOS experiment. The impactor is accelerated to high velocity by the electrical explosion of the underlying Aluminum bridge foil. When the bridge foil explodes, it punches out a section of the impactor and insulating layers and drives them up the evacuated barrel to strike the target. The transmission line, bridge foil, insulating layers and impactor are laminated together in a semi-rigid assembly. The barrel, target, vacuum apparatus and backing are added and the complete experiment is placed in an experiment chamber and connected to the transmission line feed from a fast capacitor bank. Primary diagnostics are a fast electronic streaking camera to measure the shock speed in the target, u_s , and a Fabry-Perot interferometer to measure the impactor velocity, u_i , and consequently the material velocity, u_m .

We chose tantalum as the test material in these proof-of-concept experiments because its EOS already has been well characterized by other means.

Design of the Electric-Gun EOS Experiments

We used two different impactor designs. In the lower-velocity experiments, the design consisted of a rolled-tantalum impactor foil 76 μm thick bonded to a Kapton backing to protect it from the plasma generated by the exploding foil. In the high-velocity experiments, the impactor was a rolled-tantalum foil 30 μm thick. We found that the thinner foils used in the high-velocity experiments were more sensitive to preheating by stray electric currents and rapidly changing magnetic fields. To protect them from preheating, we bonded the high-velocity foils to a Kapton-aluminum-Kapton sandwich. Both impactor designs were in turn bonded to an aluminum exploding foil.

Figure 2. Electronic streak camera record from a typical EOS experiment. The sketch shows the projectile and targets to scale, just prior to impact. From the step in the shock breakout signal we got $u_s = 8.01 \pm 0.3 \text{ km/s}$. The Fabry-Perot measured $u_i = 7.78 \pm 0.1 \text{ km/s}$.

The targets consisted of tantalum foils two to three times the thickness of the impactors. Steps machined in the front surface of the targets enabled us to determine the shock velocity by measuring shock transit time across an individual step.

The primary diagnostics consisted of two Imacon image-converter cameras operated in the streak mode. In one camera, the slit aperture was aligned over the

target steps and a glass flasher block (which produces a flash of light when it is hit and shocked). At pressures of 0.1 TPa or more, shock temperatures are high enough to produce thermal light emission that can be detected by a fast streak camera at the instant of impact on the glass or when the shock arrives at the free surfaces of the metal target. From this record, we determined the time of shock breakout at two different distances through the target. Figure 2 shows a typical record from this camera. From the record of the impact on the glass we can determine the flatness and smoothness of the impactor, the presence of debris, etc.

The second camera was used in conjunction with a Fabry-Perot velocity interferometer³ to obtain a continuous history of the impactor velocity.

Figure 3. Rise time of the shock breakout signal. Lower camera designs could decrease the uncertainty in u_s to about 1%.

We can measure the impactor velocity and consequently the material velocity u_m to $\pm 1.2\%$ with the Fabry-Perot interferometer. Errors in the shock velocity u_s result primarily from errors in measuring the step height of the target (about $\pm 0.6\%$) and from the intrinsic resolution of the camera, from ± 1 to $\pm 5\%$, depending on the camera model and the streaking rate.

In Fig. 3, we show a microdensitometer trace of the shock breakout signal. The rate of rise of the signal is 0.32 density units/ns, and since the film graininess is about ± 0.05 density units, the uncertainty in locating the shock breakout time, i.e., the mid-point on the rising signal is about $\pm 0.12 \text{ ns}$.

The shock transit time over the step distance is about 4 ns in the thin targets and 10 ns in the thick targets. The uncertainty in the transit time is thus about $\pm 3\%$ in the high pressure thin target data and about $\pm 1.5\%$ in the lower pressure thick target data.

Departures from planarity of the impactor and target must be measured and, if they are significant, a

correction must be made. The magnitude of this correction is determined by the deviation from planarity in the immediate vicinity of the step in the target.

In measuring the shock transit time, a rarefaction affected zone near the step must be avoided because the shock pressure and speed will be unrepresentative in this region. This zone will be from one to two times the step height, as shown in Fig. 2. In our EOS experiments, the step heights are only about 30 μm . Corrections for deviations from planarity over distances of this order (60 μm) are very small, on the order of 0.1 ns and are comparable to the resolution of the camera system.

In our most accurate experiments, the estimated error in u_m was $\pm 1.2\%$ and in u_s $\pm 2.5\%$, leading to errors of $\pm 2.7\%$ in pressure and $\pm 3.3\%$ in volume.

Figure 4. The shock Hugoniot of Tantalum.

Experimental Results

Our earliest electric-gun results were obtained with relatively thick impactor foils (76 μm), which reduced impact velocities enough to allow comparison of our data with those reported by others.⁴ Our shock Hugoniot data agree with those obtained with a two-stage gas gun up to its performance limit, about 440 GPa.⁵ as is shown in Fig. 4.

More recent experiments used thinner (30 μm) tantalum impactors and achieved velocities up to 9.7 km/s, extending the Hugoniot curve for tantalum up to 780 GPa. All of our data fall within 2.7% root-mean-square of a straight line fit to the gas-gun data.

Conclusions

We have established the feasibility of making direct ultra-high pressure measurements of the shock Hugoniot with the electric gun. We have reduced experimental uncertainties to $\pm 1.2\%$ in u_m and $\pm 2.5\%$ in u_s and have reproduced existing data to within experimental error.

Conservative extrapolations from our system's current operating conditions indicate that pressures of from 1.1 to 1.5 TPa could be achieved in various dense materials with little difficulty.⁶ The extremely high velocities we have achieved with plastic impactors lead us to believe that even higher pressures can be reached.

References

1. H. H. Chau, G. Dittbenner, W. W. Hofer, C. A. Honodel, D. J. Steinberg, J. R. Stroud and R. C. Weingart, *The Electric Gun: A Versatile Tool for High Pressure Shock Wave Research*, Rev. Sci. Instrum. **51**, 0028 (1980).
2. C. E. Ragan III, *Shock Compression Measurements at 1 to 7 TPa*, Physical Review A, **25** No. 6, p. 3360.
3. D. R. Goosman, et al, *Measuring Velocities by Laser Doppler Interferometer*, LLNL Energy and Technology Review, UCRL-52000-79-3, March 1979.
4. K. E. Froeschner, et al, *Shock Hugoniot Measurements Using an Electric Gun, in Shock Waves in Condensed Matter - 1981*, AIP Conference Proceedings No. 73, p. 174.
5. A. C. Mitchell and W. J. Nellis, J. Appl. Phys. **52** 3363 (1981).
6. LLNL, Energy and Technology Review, UCRL-52000-82-12, Dec. 1982, p. 11.

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