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SHOCK COMPRESSION OF LOW-DENSITY FOAMS

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Shock compression of very low density micro-cellular materials allows entirely new regimes of hot fluid states to be investigated experimentally. Using a two-stage light-gas gun to generate strong shocks, temperatures of several eV are readily achieved at densities of roughly $0.5\text{--}1\text{ g/cm}^3$ in large, uniform volumes. The conditions in these hot, expanded fluids are readily found using the Hugoniot jump conditions. We will briefly describe the basic methodology for sample preparation and experimental measurement of shock velocities. We present data for several materials over a range of initial densities. This paper will explore the applications of these methods for investigations of equations of state and phase diagrams, spectroscopy, and plasma physics. Finally, we discuss the need for future work on these and related low-density materials.

INTRODUCTION

Novel states of hot and highly expanded fluids can be achieved by shock compression of low-density micro-cellular materials. The irreversible nature of the shock process and the subsequent increase in entropy lead to high temperatures in the post-shock state.^{1,2} If the size of the cells (pores) in the material is small (*viz.* for pore diameter δ , shock velocity u_s , $\delta/u_s \leq 0.1$ ns, the typical time resolution of this work), the samples can be considered to be homogeneous and in local thermodynamic equilibrium after shock passage. For the typical foams reported on here, δ/u_s ranges between a few ps to 100 ps. Thus, the use of micro-cellular materials allows us to treat these materials as fluids after shock passage. Since these states are prepared by shock compression, rather than by expansion from a reference state, we can use the simple conservation conditions expressed by the Rankine-Hugoniot equations to determine the state of the material. With accurate dynamic measurements of the shock and/or particle velocities and careful sample preparation, very high accuracy has been achieved. The states we can reach are beyond the reach of other methods, and can be applied to a variety of materials in compression, or in subsequent expansion, as shown in Figure 1. Using the materials and methods described here, we can study dissociated, partially ionized fluids that are highly expanded relative to normal solid density. We will first briefly describe the experimental methods, and then emphasize material properties and applications.

EXPERIMENTAL METHODS

Most of the applications we will describe here are based on the measurement of shock velocity in the

low-density samples, which is described in detail elsewhere.³ We use a two-stage light-gas gun to generate the shock waves in the foam samples by impact of planar metal plates. If the impactor velocity and the initial density are also measured, the P,p,E state of the material can be determined using the Hugoniot equations. Shock velocity is found by measuring the transit time of the shock across a machined cylindrical step of known height. The material behind the shock front is hot and very luminous. The appearance of the luminosity at the free surfaces of the

Figure 1. A typical Hugoniot curve for a low-density material is shown by the bold line. This path contrasts sharply with the principal Hugoniot of the same material shocked from nominal reference density. The low-density Hugoniot accesses high temperature, low-density states.

Figure 2. Silica aerogel shock compression data for two values of initial density, 0.128 and 0.06 g/cm³. Also shown is a best-fit linear fit to the data.

sample is used to indicate shock arrival times at those surfaces. To increase the contrast of these events, we typically plate the free surfaces with a 200 nm thick Au layer. This layer also serves to increase the accuracy of the optical backscattering method used to measure the step height and roughness. For example, our usual step height is 2.5 mm, with an RMS deviation of 5 μ m or less across the 20 mm diameter area we observe. After mounting in a sample holder, the targets are evacuated to less than 10⁻⁶ torr.

An electronic image-converter streak camera is used to measure the shock arrival times across on image of the free (rear) surfaces on the entrance slit of the camera. A pulse train from a mode-locked argon-ion laser is used to provide a real-time calibration of the camera sweep while the shock arrival events are recorded. Tilt and bowing of the projectile arising from rapid acceleration in the gun are compensated for using a four-parameter fit to the time *vs.* position shock arrival data. The typical accuracy for shock velocity is better than 0.5% at two-standard deviations. The impactor velocity is measured using flash x-radiography.⁴ The initial densities of the samples are determined volumetrically. Sound velocities can also be determined in these measurements by observing the angle of the rarefaction that reduces the planar shock diameter.⁵

In some experiments, we measure the shock temperature of the samples. In this case, the samples are simple cylinders, and not Au plated. Thermal emission from the shock front is recorded with a system of six fast photomultipliers, coupled to the target with a multi-channel fiber-optic bundle. Each photomultiplier is fitted with a narrow band-pass (20 nm FWHM) filter in the range 250–700 nm. We can also record the emission using a streaked spectrographic system,⁶ or

can record “snapshot” spectra on a 1024-element linear diode array fitted to a low-dispersion spectrograph. These last methods can serve as a check to the black-body assumption. The system is absolutely calibrated in intensity and wavelength using a standard lamp. This allows us to determine both temperature and emissivity in the experiment. Besides the convenience of the fiber-optic approach, the constant solid angle for detection provides freedom from any time-dependence of the signals due to depth-of-field effects, which commonly plague imaging systems. The system we use is also sensitive, with an equivalent f-number of 2.5. The photomultipliers have roughly 1 ns rise time, and are recorded with 1 GHz bandwidth digital oscilloscopes.

SHOCK COMPRESSION OF SILICA AEROGELS

Silica aerogel is a transparent, rigid foam material with a typical pore diameter of 10 nm. It is a glassy foam, and is readily machinable with single-point diamond tools. The initial density of silica aerogel can be controlled during preparation in the range 0.006–0.9 g/cm³. We performed the first shock compression experiments on this material with $\rho_0 = 0.128$ g/cm³ about a decade ago.² During the past several years, we have determined the Hugoniot EOS for two different nominal initial densities of this material, as well as measurements of shock temperature. For nominal initial densities of 0.06 and 0.128 g/cm³, we found that the Hugoniot in the u_s - u_p plane is linear, $u_s = C + Su_p$, and that both materials have the same values of C and S . This is remarkable result, since the final states after shock passage differ markedly for these two materials. These data are plotted in Figure 2. The best fit to the data is for $C = -46$ km/s, and $S = 1.16$. As Grover, *et al.* have pointed out, the reason is that the equation-of-state is dominated by thermal pressure, and can be characterized by a single integral Grüneisen coefficient, independent of the initial density of the materials.⁷

This suggests that measurements of shock temperature will be important for these materials. Space does not permit a tabulation of these results, but temperatures ranged between 0.3–3 eV in our experiments. We also observed an interesting effect worth mentioning. The initial densities of the samples are so low that it takes on the order of 50 ns to become optically thick and the rise time of the signals varies with wavelength. Since the thickness of the emitting region increases linearly with time, measuring the rise time of the signals determines the opacity of the partially ionized SiO₂ plasma generated by shock compression. This is similar to experiments performed 20 years ago by Bespalov, *et al.*,⁸ but in a material which is initially a rigid, molecular solid.

Figure 3. Hugoniot data for shocked carbon aerogels of two different initial densities. Both data sets are fit well by a linear u_s - u_p relation, $u_s = C + Su_p$. The units of C given in the figure are km/s.

CARBON AEROGELS

Carbon aerogels are made by oxidizing resorcinol-formaldehyde (RF) aerogels at high temperatures in air. Since the structure has open cells, the RF aerogel can be completely transformed into an apparently glassy pure carbon foam, with a typical cell size of 10 nm. Carbon may have interesting high temperature fluid and electronic properties. The phase diagram in the region of the graphite-diamond-fluid triple point is still uncertain, as is the slope of the diamond melting line. Shock compression of carbon aerogels has the potential to explore a much wider range of the P-T phase diagram than more usual methods. The graphite melting line and high temperature fluid states are reached for initial densities of roughly 0.1-0.5 g/cm³; densities above about 0.7 g/cm³ may access both the graphite-diamond transition as well as the diamond melting line. We have performed experiments on two carbon aerogels, with initial densities of 0.12 and 0.9 g/cm³. The results for both are linear in the u_s - u_p plane (Figure 3), but in contrast to the silica aerogel data, the values of C and S are different for the two materials. This indicates that thermal pressure is not dominant for the higher density carbon aerogel. Comparisons to detailed statistical mechanical models such as the CHEQ⁹ code, show good agreement with the equilibrium phase boundaries. However, the curvature of the actual Hugoniot curve shown in Figure 4 for the higher density carbon aerogel in the P-p plane does not agree with calculations. This may be due to effects of the foam structure and strength, and to the potential existence of a mixed-phase region along the path of the Hugoniot.

Figure 4. Hugoniot data for carbon aerogel with nominal $\rho_0 = 0.9 \text{ g/cm}^3$, compared the calculation using the CHEQ code (open circles). The discontinuity in the calculated curve is the graphite-diamond transition.

LOW-DENSITY FOAMS AS EOS STANDARDS

Once the Hugoniot EOS of a low-density material is accurately determined, that material may be used to advantage to investigate other materials. A strong shock may be easily generated in a metal plate. If a foam sample is mounted in contact with the rear (non-impact) surface of the metal, the shock pressure is reduced when the shock arrives at the metal-foam interface. The final state of the metal is on an isentropic release path from the initial shocked state. A measurement of the shock velocity in the low-density sample determines the final release state of the metal. A result for aluminum initially shocked to 78 GPa, and released to 5 GPa, is shown graphically in Figure 5. The data agree to better than 0.8% with a release model calculated by Grover.¹⁰ In more recent experiments, we have been able to measure the release state with an uncertainty of better than 0.5% in the P- u_p plane. This method may be used to advantage for porous geologic materials, for example, for which the use of dense gases as analyzers for the release state is impractical. This is also the case for very small samples, such as those in laser-driven shock experiments, for which the high gas pressures required can not be used.

Layers of well-characterized low-density foams may be used to increase the transfer of mechanical energy in shock compression experiments on samples of extremely low density. We have recently performed shock compression experiments on tetraphenyl pentene (TPX) with an initial density of 0.007 g/cm³. Using a "buffer" plate of polyacrylonitrile (PAN),

Figure 5. Schematic of a shock and release experiment in aluminum. The initial shock was to 78 GPa on the solid curve. The isentropic release path is shown dashed, and the final pressure was about 5 GPa. The data (solid circle) is compared to calculations by Grover using the Gray code (open square). The inset is a magnified plot showing good agreement with the experiment.

whose Hugoniot we had determined, allowed us to reach twice the pressures in the TPX samples than we could achieve by direct impact. The use of such a plate has also been suggested as a way to achieve very hot plasma states generated by shock compression of gases.¹¹

DISCUSSION

The methods for studying low-density materials by shock compression are now relatively mature. I will briefly present some ideas for further work. There remains a need for experiments and theory in the low pressure "crush-up" regime of these materials, where strength effects are important and the materials remain cool. This has technological importance, as these materials are used as "soft" materials to collect space-borne debris and small meteoric rocks. In this regime, the influence of cell size may be important. At present, there are no "global" models for the response of these materials that are consistent with experiment over a wide range of pressure and temperatures. More optical studies are warranted. Reflectivity measurements on hot, fluid carbon may be able to determine the conductivity, an issue that remains in doubt. Strong, well-resolved (and time dependent) emission spectra have been observed in PAN, possibly indicating that non-equilibrium chemi-

cal effects and kinetics may be observed. On the other hand, the low densities reached may allow one to probe behind the shock front much further than can be done in normal condensed media. These materials are easy to dope with small amounts of impurities. This may open up the possibility of studying plasma physics of high-Z elements in strongly coupled plasmas using x-ray spectroscopy.

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