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Isentropic compression experiments to 1 Mbar using magnetic pressure

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Abstract

Isentropic compression experiments that utilize intense magnetic fields to compress samples have been designed, developed and performed. The technique has been shown to work to pressures of more than 1 Mbar on Sandia National Laboratory's Z pulsed power machine. We are extending the technique to use high-explosive pulsed power.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Accurate data on material properties at high pressure are essential for constraining theoretical equations of state (EOS). Data in the megabar regime are usually shock Hugoniots, produced one density–pressure point at a time. Also of general interest are compression isentropes, but isentropic data at pressures above 100 kbar are rare due to the difficulty of smoothly loading a target without also inducing a shock [1].

A technique that does deliver a shockless compression is the use of magnetic pressure in a high-current circuit. If the current is smoothly controlled, the available magnetic pressure is also smooth via

$$P_{mag}(t) \propto B(t)^2 \qquad \text{or} \qquad P_{mag}(t) = 2\pi J(t)^2 \qquad (1)$$

where B is the magnetic field; here P_{mag} is in megabars and the current density J is in units of 10^7 A cm^{-1}. This technique [2] has been adapted to the 20-MA Z pulsed power machine at Sandia National Laboratories, a toroidal accelerator normally used for z-pinch experiments. Z produces a current profile $B(t)$ that rises linearly with time over 100–200 ns. The target load configuration consists of four parallel anode–cathode faces, each of which is an EOS experiment that produces a continuous pressure–density isentrope from $P = 0$ up to a peak pressure determined by the machine current. Each experiment involves a pair of samples of different thickness. The EOS is determined by examination of wave profiles of the surfaces of both samples and application of conservation relations [3].

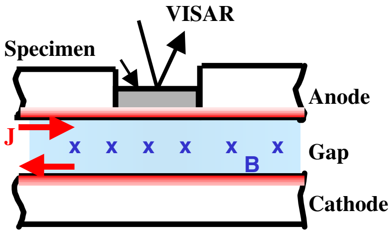

Figure 1. Sketch of experimental setup.

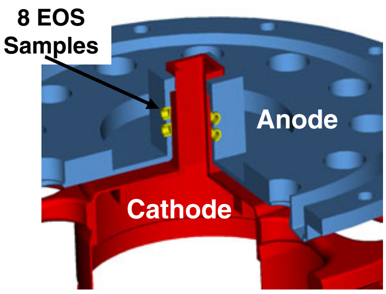

Figure 2. ICE experiment on Z.

2. Experiments

Figure 1 shows a sketch of the experimental set-up. A current is passed through a short circuit with a gap between the anode and the cathode. The magnetic field in the gap exerts pressure on both the anode and the cathode. The pressure pulse is transmitted through the anode and into target specimens bonded to the anode. The surface behaviour of the specimens is measured using a VISAR (velocity interferometer).

The drive must be planar and uniform. On Z this was accomplished by bringing the current into a concentric square anode–cathode configuration. Each of the four faces of the 'square short' has an area capable of holding two specimens. Two specimens of the same material but different thicknesses are required to obtain a pressure–density EOS curve, so four different EOS experiments can be performed simultaneously on one pulsed power shot. The maximum current on Z, about 20 MA, leads to a current density of $\sim$4 MA cm^{-1} and a final peak pressure of around 1 Mbar. A two-face configuration that increases the current density has been demonstrated to over 1 Mbar.

Isentropic compression experiments (ICE) have been performed on several materials, including Cu, Al, Fe, Ta, Be and organic compounds, up to peak pressures that vary from 200 kbar to over a megabar [4]. For example, figure 3 shows results for Cu up to 280 kbar. There are four experimental curves that are compared with Hugoniot data and a theoretical isentrope. At these pressures, the principal Hugoniot and principal isentrope are nearly coincident. Typical uncertainties in the data are 2–3%. Data on Al and Be extend to 1.1 Mbar.

One limitation with Z is the current profile itself. The compression wave will at some point evolve into a shock wave in the sample. One of us (JRA) has suggested that a loading wave that is not linear but has a long, low-pressure foot followed by a more rapid rise will delay the wave's evolution into a shock, allowing thicker samples and higher accuracy. The machine characteristics of Z have been modified to accommodate a current profile to approximate the desired shape. This has allowed experiments on 'softer' materials, like plastics and high

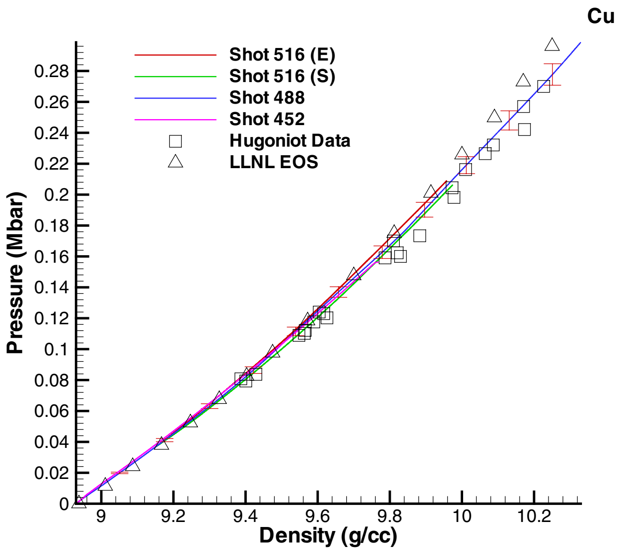

Figure 3. Experimental isentropes to 280 kbar in Cu using magnetic compression.

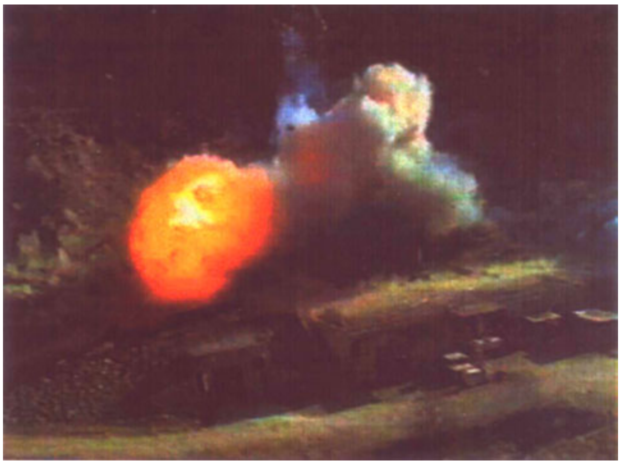

Figure 4. A development test of HEPP ICE at LANL.

explosives, where, without current pulse shaping, the ramping pressure pulse would rapidly convert into a shock.

We are currently exploring the possibility of employing shaped current profiles with the use of high explosive pulsed power (HEPP) devices. HEPP offers several advantages over conventional, machine-based pulsed power. Higher currents are available for higher pressures; 10 Mbar or more appears possible. At higher currents (and pressures) the samples have to be larger, as must the anode that the samples rest on. HEPP will permit these larger configurations. Also, the current shape can be designed for the particular sample material used on each shot. HEPP ICE is now undergoing development and assessment as a Lawrence Livermore—Los Alamos collaboration. Figure 4 shows a photo of a development test of an HEPP ICE shot at Los Alamos.

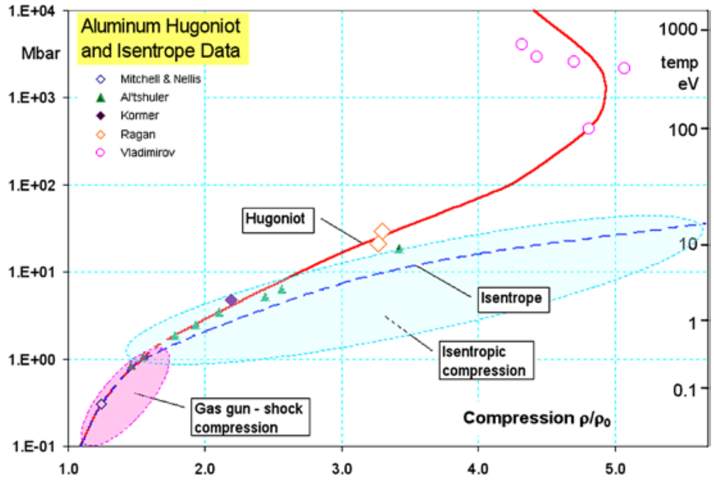

Figure 5. Pressure–density plot of aluminium showing Hugoniot data and the isentropic region.

3. Conclusions

These experiments make it possible to obtain off-Hugoniot EOS data at high pressure (see figure 5). In addition, since the wave trajectory may cross several material phases from low to high pressure, phase transitions will be evident as long as there is a volume change at the phase boundary. Using this technique, the α–ε transition in iron has been observed in these experiments [2].

Acknowledgments

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