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ScienceDirect

High Energy Density Physics 2 (2006) 113−125

High Energy Density Physics

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High pressure, quasi-isentropic compression experiments on the Omega laser

K.T. Lorenz*, M.J. Edwards, A.F. Jankowski, S.M. Pollaine, R.F. Smith, B.A. Remington

Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Received 2 June 2006; received in revised form 2 August 2006; accepted 2 August 2006
Available online 28 August 2006

Abstract

The high energy density of pulsed lasers can be used to generate shockless loading in solids to high pressures and compressions but low temperatures. [J. Edwards, K.T. Lorenz, B.A. Remington, S. Pollaine, J. Colvin, D. Braun, B.F. Lasinski, D. Reisman, J.M. McNaney, J.A. Greenough, R.Wallace, H. Louis, D. Kalantar, Laser-driven plasma loader for shockless compression and acceleration of samples in the solid state, Phys. Rev. Lett. 92 (2004) 075002.] We have used the Omega laser to extend the capabilities of this technique to multi-Mbar pressures and compressions approaching a factor of 2 in aluminum foils. The energy from a 3.7 ns laser pulse is used to drive a strong shock through a 200 μm polystyrene disc. The disc material unloads from a high-pressure state and expands across a 300 μm vacuum gap where it stagnates against the sample to produce a smooth, monotonically increasing load with rise times from a few to ∼20 ns. Ramped compression waves having peak pressures of 14−200 GPa (0.14−2.0 Mbar) and peak compressions ρ/ρ_0 of 1.1−2.0 were generated in the aluminum samples using laser pulse energies of 400 J to 2 kJ. Wave profiles from a series of successively thicker targets loaded to 120 GPa show the evolution of the high-pressure compression wave within the sample. The initial loading in the sample is shockless, and develops into a shock at a depth of 20−25 μm. We compare these wave profiles with hydrodynamic simulations from which we extract material temperatures and plastic strain rates behind the compression wave. Limitations and future prospects for this new shockless loading technique are discussed.

Keywords: Isentropic compression; ICE; Equation of state (EOS); Aluminum

1. Introduction

High energy density (HED) conditions in matter can be created by heating samples to high temperatures, or at low to moderate temperatures, by compressing matter to high densities. The former can be achieved by heating a sample rapidly to high temperature T, such as with a laser, or by driving a very strong shock through the sample. The latter conditions, namely, cool dense states of matter, apply to planetary interiors, for example, and have been experimentally more difficult to achieve. Creating pressures $P > 100$ GPa (1 Mbar), which is required to compress solid density matter, without shocking (so as not to heat the sample) is experimentally challenging. Creating several 100 GPa, or even pressures $P > 100$ GPa in a quasi-isentropic compression, which is relevant to planetary core conditions [12] has not yet been achieved in the laboratory. These conditions are interesting in their own right, since a plethora of phase transitions is predicted, as the lattice seeks to accommodate the state of high compression, as illustrated in Fig. 1 for aluminum [1,2,7,25].

We show in Fig. 1 an illustrative $P-T$ phase diagram for Al [2,38] superposed with the melt curve (upper dotted curve), the $P-T$ path for the principal Hugoniot (heavy dotted curve), a path representing a staged shock, off-Hugoniot loading (dot-dashed curve), and the $P-T$ path for the room temperature isentrope (dashed curve). We are developing a quasi-isentropic loading capability, with the goal of being close to the room

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* Corresponding author. Lawrence Livermore National Laboratory, 7000 East Avenue, P.O. Box 808, L-282, Livermore, CA 94551-0808, USA. Tel.: +1 925 424 4200; fax: +1 925 424 3281.
E-mail address: lorenz3@llnl.gov (K.T. Lorenz).

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doi:10.1016/j.hedp.2006.08.001

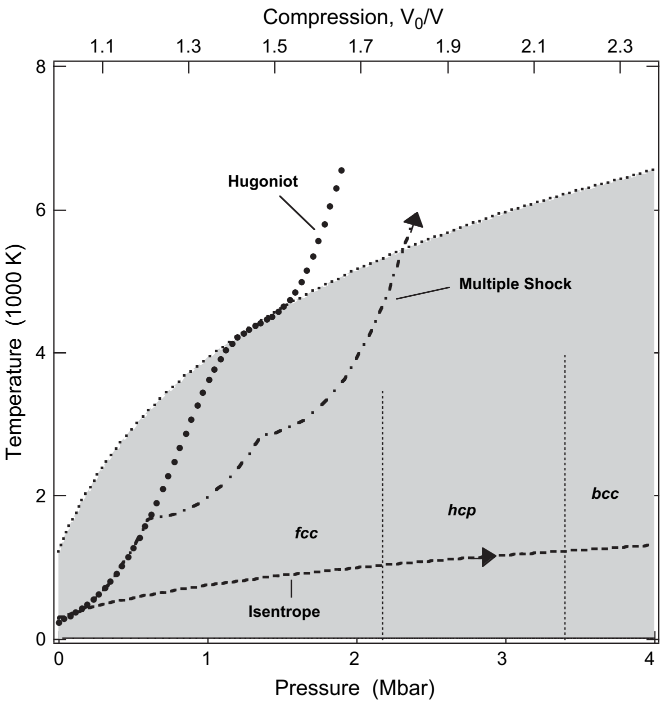

Fig. 1. Schematic pressure–temperature (P–T) phase diagram for Al. The lower horizontal axis gives pressure, and the upper horizontal axis gives compression assuming the room temperature isotherm from Ref. [7]. Superposed are curves showing the melt temperature versus compression (upper dotted curve bounding the shaded region), T versus P along the principal Hugoniot (heavy dotted curve), three-staged shock T versus P trajectory (dot-dashed curve), and the P–T curve along the room temperature isentrope (dashed curve). The shaded region corresponds to the P–T space for Al in the solid state [2]. The fcc-to-hcp and hcp-to-bcc transitions are based on the predictions and observations described in Refs. [1,7,25].

temperature isentrope, to be able to access very high pressure, low temperature regimes in the solid state [31,32]. Note, from Fig. 1 it is clear that multiple high-pressure phases of Al, for example, will be accessible with such a loading path, but totally missed along the principal Hugoniot. It is hoped ultimately with the NIF laser [17] to be able to access new regimes of solid-state matter that have never before been observed in the laboratory.

Several approaches for generating quasi-isentropic loading have been pursued by various groups. A high energy explosives (HE) approach was the first that we are aware of to show how quasi-isentropic, dynamic compression up to several ×100 kbar could be achieved [3,4]. More recent quasi-isentropic work with this HE approach have achieved peak pressures over 700 kbar [28]. An approach using graded-density impactors on a gas gun is also being developed [27]. An elegant approach using an increasing current to generate a magnetic pressure on the Z facility has led to quasi-isentropic compressions at peak pressures of 185 GPa [13,16,29] with hopes of pushing this peak pressure yet higher. The technique we are currently developing resembles the original HE approach of Barnes, except with the HE-initiated shock being replaced with a laser-driven shock to increase the energy density and hence, peak pressure. As will be described below, we have reached peak pressures of 200 GPa with this quasi-isentropic drive, with hopes of increasing this by an order of magnitude to 1000–3000 GPa on NIF [31,32]. With these quasi-isentropic loading techniques being developed by multiple groups around the world, the ability to access and probe new regimes of solid-state matter at extreme pressures will be realized.

This paper is organized as follows. The experimental description and methodology are given in Section 2, and in Section 3 we present our results. A discussion is given in Section 4, and we summarize in Section 5.

2. Experimental description

In this section we describe our laser based experimental technique for reaching high pressures in a quasi-isentropic compression. A schematic of the target package and experimental arrangement is shown in Fig. 2. Energy is deposited onto the front surface of a plastic reservoir, resulting in rapid heating and pressurization of the reservoir material. This launches a strong shock moving through the reservoir, effectively converting the laser energy into the necessary mass momentum for applying a load to the sample positioned "downstream" across a vacuum gap. When the shock reaches the gap, the reservoir material unloads nearly isentropically into vacuum and expands across the gap as a weakly ionized gas. The rapidly expanding reservoir material will then stagnate and accumulate against the sample, compressing it smoothly and monotonically in time, until the reservoir material is depleted.

To characterize the drive, an aluminum sample with an LiF window is used. The spatially resolved particle velocity of the Al–LiF interface is measured as a function of time with a line VISAR (velocity interferometer for any reflector) [9]. These measurements provide a continuous, in situ particle velocity record of the aluminum under dynamic loading conditions. Because the equation of state (EOS) of aluminum is well known up to pressures of a few Mbar [16,20,23,24,26,36], the particle velocity records, $u_p(t)$, can be used to extract loading pressures, $P(t)$, at the front of the samples [14,16]. Details on the conversion of the VISAR records to pressure histories are given below.

The targets, shown in Fig. 2, consist of a reservoir and an Al–LiF target package separated by a precision spacer. Reservoirs consisted of a 28 µm thick polyimide ablator ($C_{22}H_{10}N_2O_5$, density $\rho = 1.42$ g/cm^3) glued to a 170 µm thick layer of 12.5% brominated polystyrene ($C_8H_6Br_2$, density $\rho = 2.00$ g/cm^3). The bromine dopant functions as a preheat shield by absorbing X-rays formed in the laser ablation region at the front of the target. In addition, the dopant increases the average density of the reservoir material, resulting in a softer loading rate in the sample [11]. The polyimide serves as the laser ablation material. The ablation layer should have components of low atomic number in order to avoid generating hard X-rays, which could preheat or melt the front surface of the sample before the loading process begins. The reservoir was glued to a 5 mm outer diameter polystyrene spacer precision milled to a thickness of 300 µm, and bored to an inner