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Laser driven shock wave experiments for equation of state studies at megabar pressures

H C Pant[1], **M Shukla**[2], **V K Senecha**[2], **S Bandyopadhyay**[2], **V N Rai**[2], **P Khare**[2], **R K Bhat**[2], **N K Gupta**[3] **and B K Godwal**[3]

[1] Guest Scientist, Centre for Advanced Technology (CAT), Indore-452013, India
[2] Laser Plasma Division, Centre for Advanced Technology (CAT), Indore-452013, India
[3] High Pressure Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai-400085, India

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Abstract

We present the results from laser driven shock wave experiments for equation of state (EOS) studies of gold metal. An Nd:YAG laser chain (2 J, 1.06 μm wavelength, 200 ps pulse FWHM) is used to generate shocks in planar Al foils and Al + Au layered targets. The EOS of gold in the pressure range of 9–13 Mbar is obtained using the impedance matching technique. The numerical simulations performed using the one-dimensional radiation hydrodynamic code support the experimental results. The present experimental data show remarkable agreement with the existing standard EOS models and with other experimental data obtained independently using laser driven shock wave experiments.

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

1. Introduction

Equation of state (EOS) data [1–3] are an important input to inertial confinement fusion, astrophysics and hydrodynamic codes used for the simulations of fission, fusion devices and their effects. Impedance matching technique has been used by Koenig *et al* [4] to test the relative consistency of the EOS of two materials, or, alternatively, to measure an EOS point for one of the materials, using the EOS of the other material as a reference. In fact, by using the impedance matching technique, the EOS of gold has been tested and has been found to be consistent with the SESAME data up to 35 Mbar [5].

We performed our first laser driven shock wave experiment at CAT for EOS studies of aluminium and gold used in planar foil target configurations with Al as reference material facing the laser beam and Au as test material on the rear side.

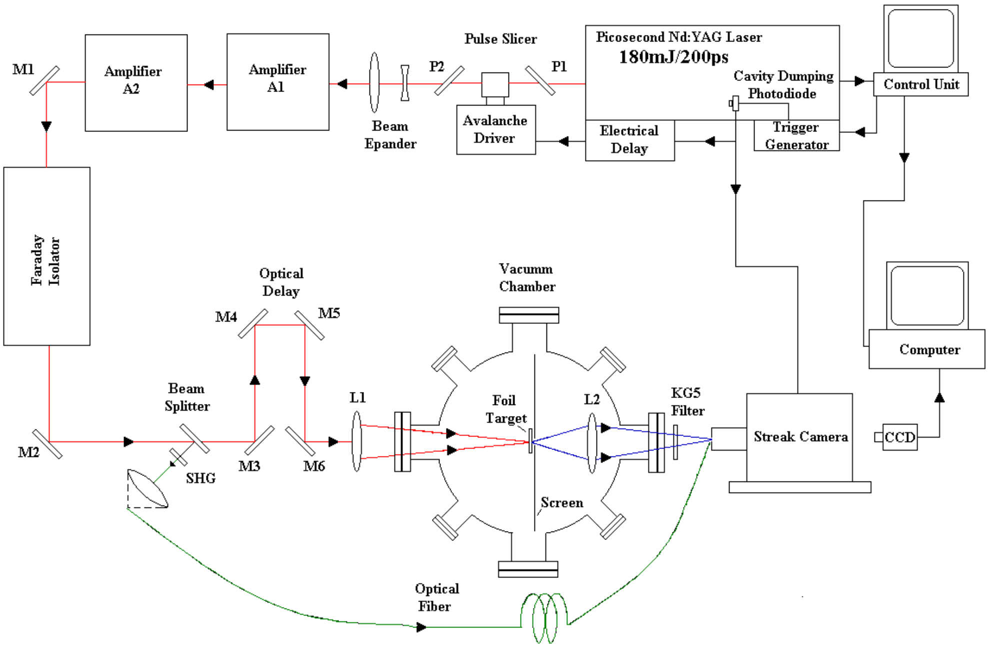

Figure 1. Schematic diagram of the experimental set-up: $M_1, M_2, \ldots, M_6$ are fully reflecting mirrors; L_1 is the focusing lens; L_2 is the imaging lens.

2. Experimental set-up

An Nd:YAG laser chain (2J, 200 ps FWHM) consisting of a modified Pico second oscillator for single shot operation, two silicate glass amplifiers and a Faraday Isolator, with a good beam quality is used as a driver (figure 1). An external pulse slicer has been designed to improve the contrast ratio of the laser pulse.

The shock luminosity signal at the rear surface of the target during shock unloading is recorded with a visible (s-20) streak camera having temporal and spatial resolution of 20 ps and 100 μm respectively [6]. When the shock unloads at the rear free surface thermal radiation is generated. A fiducial signal that serves as a marker for the arrival of laser pulse on the target front surface is also recorded along with the shock luminosity signal. The synchronization between the laser pulse for shock generation and the fiducial signal is done with the help of fully reflecting mirrors M3–M6 as shown in figure 1.

2.1. Shock velocity measurements and determination of pressure in reference material: planar Al foils

A typical experimental observation of shock emergence seen as strong luminosity as recorded by streak camera is shown in figure 2.

The shock velocity and the particle velocity follows a linear relationship for a wide range of pressures. As per the LASL data book [8], this relationship can be written as

$$u_s = 0.5386 + 1.339u_p \tag{1}$$

This relationship is used to calculate the particle velocity u_{p1} corresponding to the experimentally found shock velocity ($u_{S1} = 2.096 \times 10^6$ cm s^{-1}). The particle velocity turned out to be

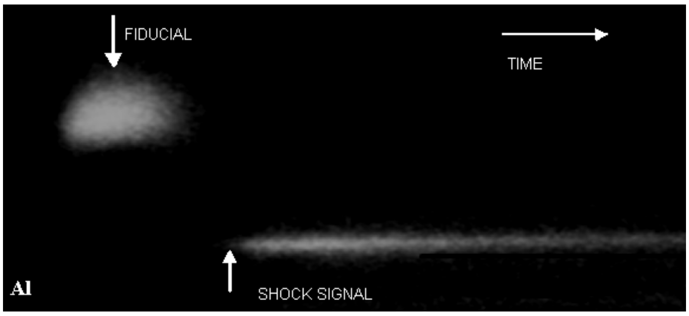

Figure 2. A typical streak camera record of a luminosity signal (picosecond resolution) captured through a CCD camera at the time of shock break-out from the rear surface of a 5 μm thick Al foil.

1.163×10^6 cm s^{-1}. Once both the value of particle velocity and shock velocity are known, the pressure can be calculated from the standard Hugoniot relationship:

$$P = \rho_0 u_s u_p \tag{2}$$

The pressure is found to be $P = 6.586$ Mbar which is the final shock pressure induced in the aluminium foil in our experiment.

2.2. *Measurements of shock velocity in multi-layered targets and determination of gold Hugoniot using the impedance matching technique*

We have carried out the deposition of 1.75 and 1.5 μm thick gold layers on the rear surface of Al foil with a thickness of 5 μm, employing chemical and vacuum deposition techniques. The variation in thickness of 5 μm was of the order of $\pm 2\%$. The shock transit times were determined for layered targets of 5 μm Al + 1.75 μm Au and 5 μm Al + 1.5 μm Au at incident laser intensities of 10^{14} and 6×10^{13} W cm^{-2}, respectively. The shock velocities were found to be 1.19×10^6 and 1.02×10^6 cm s^{-1} respectively for the above-mentioned laser intensities.

The intersection of the Rayleigh line with the reflected Hugoniot gives the final state of the gold. The final pressure and the particle velocity in gold were found to be 13.47 Mbar and 0.589×10^6 cm s^{-1} for 10^{14} W cm^{-2} incident laser intensity and 9.01 Mbar and 0.465×10^6 cm s^{-1} for 6×10^{13} W cm^{-2} incident laser intensity.

3. Comparison with numerical simulations

A proper radiation hydrodynamic simulation can serve as an important tool in predicting proper target thickness that can avoid the effects of pre-heating and also ensure steady-state shock wave propagation conditions. In the present experiments, where we used thin Al foil targets of varying thicknesses, we have carried out a detailed one-dimensional (1D) numerical simulation study using the radiation hydro code MULTI [9]. Simulation results have shown that, for the experimental laser irradiation ($I = 10^{14}$ W cm^{-2}; $\lambda = 1.06$ μm; pulse FWHM = 200 ps), the base material must be thicker than 3.4 μm to reach a stationary condition. We have also noticed that the shock wave front reaches a steady-state condition at 250 ps after the start of the laser pulse and it continues in this state until it breaks out from the rear surface at 300 ps. Simulation results show that for layered targets (Al + Au) the shock pressure becomes enhanced by nearly a factor of two at the boundary of the two materials. Our experimental results (see figure 3)

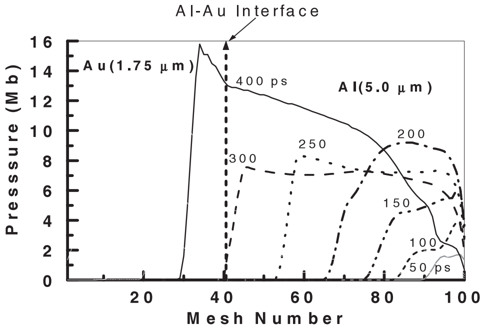

Figure 3. Shock pressure profile for Al + Au targets against the mesh number (1–40 meshes refer to 1.75 μm thick Au layer and 41–100 meshes to the Al base material). A pressure enhancement of a factor of two is seen near the interface.

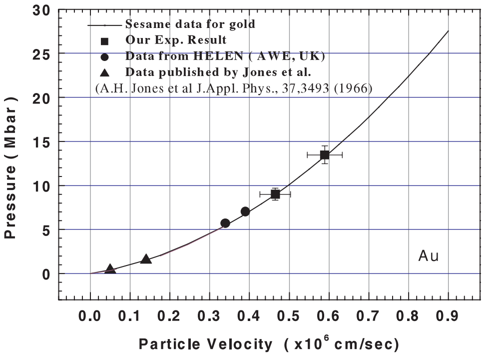

Figure 4. The experimental Hugoniot EOS data points for gold (shown by solid squares) and other previous experimental data points (solid triangles and solid circles) show good agreement with the SESAME curve.

show similar pressure enhancement in the composite target of Al + Au (5 + 1.75 μm) due to the impedance mismatch at the boundary of the two materials.

4. Results and discussion

We have compared experimental data for the shock velocity in aluminium and in gold with the SESAME data [10]. The Hugoniot curve that we have constructed for gold from experimental data also shows remarkable agreement with the theoretical data available in the LASL data book or SESAME data. The relationship between the shock velocity and the particle velocity for gold can be expressed as

$$u_s = a + bu_p,$$

where a and b are constants.

The published data from LASL gives $(a, b) = (0.312, 1.1521)$. This compares well with our experimental values of (0.312, 1.488) and (0.312, 1.495) at laser intensities of 10^{14} and 6×10^{13} W cm^{-2}, respectively. The published work of Jones *et al* [11] and the data from the indirect drive HELEN laser (AWE, UK) [12] are also presented along with our result in figure 4. Our experimental result also shows an enhancement in the pressure by a factor of two at the interface of the two materials.

5. Conclusions

The results obtained are quite consistent with the theoretical as well as experimental data published by other laboratories. The pressure amplification factor of two due to impedance matching has been derived and experimental results are in good agreement with the numerical simulations.

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