

Isentropic/shock compression and recovery methodology for materials using high-amplitude laser pulses



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ABSTRACT

A new method of subjecting samples to high-amplitude laser pulses with durations in the ns range and recovering them for characterization is presented. It is applied to tantalum monocrystals and nanocrystals that are subjected to controlled and prescribed ramp loading configurations, creating a quasi-isentropic loading in the front that is retained up to 40 μm into the specimen. This is enabled by the use of a reservoir into which six laser beams impinge simultaneously, thereby creating plasma in a reservoir, from which the pulse is launched into the metal. This technique enables, with proper wave trapping devices, the recovery of the specimens for subsequent characterization. Successful experiments conducted in the Laboratory for Laser Energetics, U. of Rochester, generated pressure pulses with initial amplitudes ranging from 15 to 110 GPa and initial durations of ~ 3 ns. The quasi-isotropic loading minimizes thermal effects at the front surface. The compression history of the recovered samples is measured using velocity interferometry from an Al-coated LiF witness target on the same shot driven by a separate, but equivalent set of laser beams. These experimental measurements are compared with computations using a radiation hydrodynamics code. Recovered samples are investigated using optical, scanning, and transmission electron microscopy. The laser damage to the surface is characterized.

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1. Introduction

Laser-compression is a powerful technique that can provide information about extreme material response to ultra-high pressures (up to and above 100 GPa) and strain rates ($> 10^8$), (e.g. [1]). In contrast with flyer-plate experiments which deliver a stress pulse that is initially square, the triangular pulse shape created by laser compression generates a pressure that decays continuously throughout the specimen. In flyer-plate experiments the initial pressure is maintained over a distance dictated by the initial duration of the top of the pulse.

The gas gun is a proven experimental tool that has enabled exploration of the extreme pressure regime for over fifty years. Recovery and diagnostic experiments have grown in sophistication. Reproducibility and control are excellent. The uniqueness of laser pulse compression in comparison with gas-gun and explosively-driven systems resides in the duration of the pulse, in the

nanosecond vs. microsecond domain. Thus, the regimes explored by the two techniques are different. There have been a number of recovery experiments conducted over the past twenty years at different pulsed laser facilities. However, compared to gas-gun experiments, recovery laser methodology is still not well established.

These recovered materials have been characterized using a host of post-shock techniques such as TEM, SEM, x-ray diffraction, and optical microscopy to determine the microstructural changes at various depths into the sample, essentially probing the material over a range of pressures, temperatures, and strain rates dictated by the pressure loading history and compression wave decay rate inside target [2–10]. Laser-driven isentropic compression experiments (ICE) furthermore allow the study of materials at even higher pressure and strain rate than traditional shock wave experiments where targets are subjected to extreme shock heating, often times to well above the melt temperature [8–13].

The Omega laser at the Laboratory for Laser Energetics (LLE) is well suited for such experiments and, with clever design, can provide multiple pieces of data per laser shot due to the large number of beams available (60) [14]. This paper describes an experimental set-up to soft-recover isentropically compressed Ta specimens while simultaneously measuring the laser drive using a VISAR witness target driven by a separate, but equivalent set of

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laser beams [15]. Results from successful experiments based on this design are presented including characterization.

2. Experimental design

The design of the sample compression and soft-recovery scheme can be divided into three parts: the ICE (Isentropic Compression Experiment) drive package, recovery tube, and target chamber geometry. Each part will be described in detail in the following sections.

2.1. Isentropic compression experiment (ICE) drive

Schematics of the Ta sample and Al/LiF VISAR target assemblies are shown in Fig. 1. The targets were designed to use direct laser ablation to achieve quasi-isentropic compression (ICE drive). By using the LASNEX radiation hydrodynamics code [16], the peak pressure exerted on the target can be calculated. The design consists of a 20 μm thick polycarbonate ablator followed by a 180 μm thick CHBr (2%) “reservoir” separated from the Ta sample by a 300 μm vacuum gap. The gap and target components are supported by a Ta washer that has two 800 μm wide by 50 μm deep radial channels to allow evacuation of the gap between the reservoir and sample. A shock wave is launched into the ablator and is transmitted to the CHBr (2%) reservoir by the laser beam. The reservoir material unloads across the 300 μm vacuum gap as a plasma. This plasma then stagnates against the sample material, exerting a pressure that increases over a rise time interval (up to ~ 10 ns), thus compressing the sample.

Samples studied here are either Ta monocrystalline cylinders 3 mm in diameter and 3 mm thick, nanocrystalline Ta specimens in 3 mm disk (~ 0.6 mm thickness) form (Grain size ~ 70 nm) (Fig. 1(a)), or LiF cylinders 3 mm in diameter and 0.5 mm thick coated with ~ 10 μm of Al (Fig. 1(b)) used as a drive witness sample.

Trapping of reflected waves is of importance in shock compression experiments to ensure that the deformation structure is generated by the primary compressive pulse and not by reflected pulses. In explosively-driven and gas-gun experiments the procedures are well established. DeCarli and Meyers [17] provide simple guidelines for the design of recovery systems in which the reflected waves are trapped. Gray [18–20] studied the effects of reflected waves in a systematic manner and concluded that the baseline design, consisting of rings for trapping the lateral release waves and a spall element at the rear of the specimen provided satisfactory momentum trapping, if properly dimensioned and machined. Computer simulations were used by Bourne and Gray [21] to design optimum recovery fixtures. In laser-driven experiments the pulse decays readily because of its short duration (~ 1 – 5 ns vs. ~ 0.1 – 2 μs in gas gun experiments). Nevertheless, the incorporation of wave trapping devices into the experimental setup is important. For this reason, a lateral momentum trap and a momentum cap were added to the nanocrystalline Ta specimens, which were disks with ~ 0.6 mm thickness. This is in essence an adaptation of the baseline design [19–21], albeit with much reduced dimensions. Five disks were stacked, inserted into a recovery tube, which acted as a lateral momentum trap, and backed by a momentum disk. The assembly is shown in Fig. 1(a).

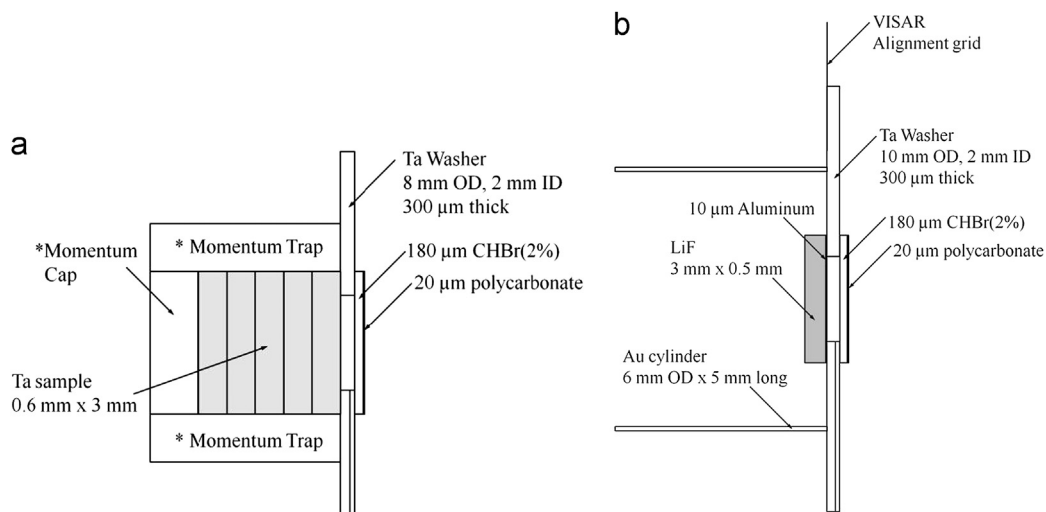


Fig. 1. ICE drive target designs for (a) Ta samples and for (b) the Al–LiF VISAR witness targets. *Optional 1 mm thick Ta momentum cap.

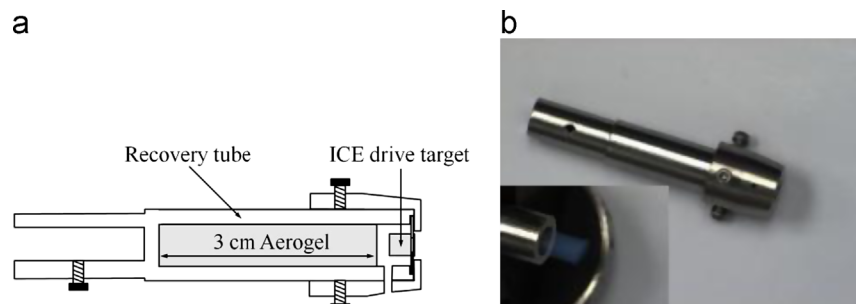


Fig. 2. (a) Cutaway drawing of the recovery tube target design showing the 3 cm long SiO_2 aerogel foam cylinder and the ICE drive target at the end and held in place by a stainless steel end cap; (b) Photograph of two recovery tubes, one fully assembled on the right; insert shows the recovery tube without cap or specimen assembly out of which aerogel cylinder protrudes.

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