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Strain anisotropy and shear strength of shock compressed tantalum measured from in-situ Laue diffraction.

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ABSTRACT: Laser driven shock experiments, performed at the Omega facility, studied the dynamic yield strength and lattice dynamics of single crystal tantalum using in-situ Laue diffraction. Tantalum samples were shocked along the [100] direction to peak stresses up to 50 GPa and probed using the bremsstrahlung radiation from an imploding CH capsule x-ray source. Diffraction spots for both the undriven and driven regions of the sample were recorded simultaneously on time-integrated image plate detectors. The strain anisotropy was measured from the position shift of the driven diffraction spot and the total strain state was found using the volumetric strain from VISAR. Yield strength measurements were inferred from the data and compared with predictions from various models, including the LLNL multi-scale strength model for Ta.

INTRODUCTION

While shock waves in metals are often assumed to behave hydrodynamically in order to simplify the analysis, there are many situations in which a material has significant strength under shock loading. In many shock experiments velocimetry (VISAR) is used as primary diagnostic, from which the stress along the longitudinal direction of the shock wave can be inferred. This leaves one with an incomplete picture of the strain state of the material. In some cases, the deviatoric stress can be determined through careful analysis of the wave profile [1], however, very high time resolution is required, which limits the application of this technique to lower strain rates. In addition, some shock experiments have utilized stress gauges mounted laterally to the shock wave, which, when combined with VISAR, yield shear stress information [2,3]. Like the wave profile analysis, lateral strain gauges have only been applied to relatively low pressure shock waves.

Recently, new techniques have been developed which allow the strain state of single-crystal materials under laser-driven shock compression to be directly measured using *in-situ* Laue x-ray diffraction [4]. Previous work examined shocks in the 0.6 to 1.8 Mbar range. This work reports the results of additional experiments that extend the *in-situ* Laue experiments to the 0.25 to 0.5 Mbar range, allowing for more direct comparisons with gas-gun results.

METHODS

The *in-situ* Laue shock experiments were performed at the Laboratory for Laser Energetics Omega Facility. A single beam

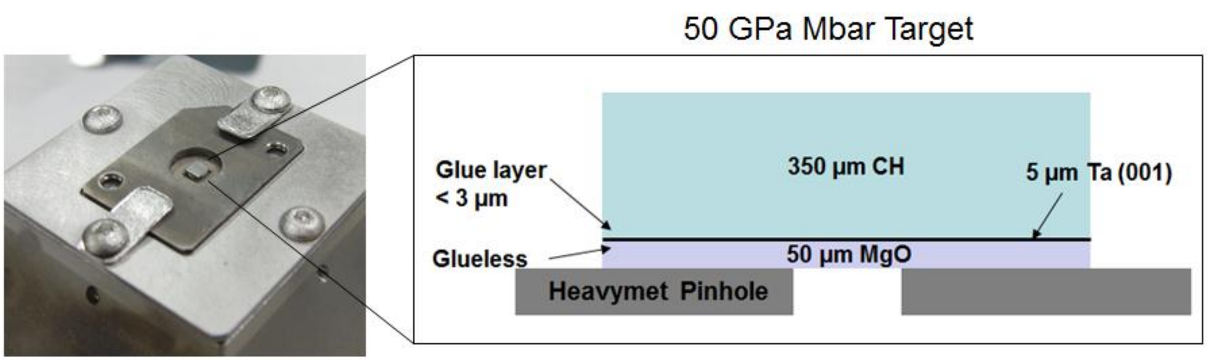

Figure 1 Picture of Laue target package mounted on the BBXRD diagnostic (Left) and detail sketch of the ablator, single-crystal, tamper package (right).

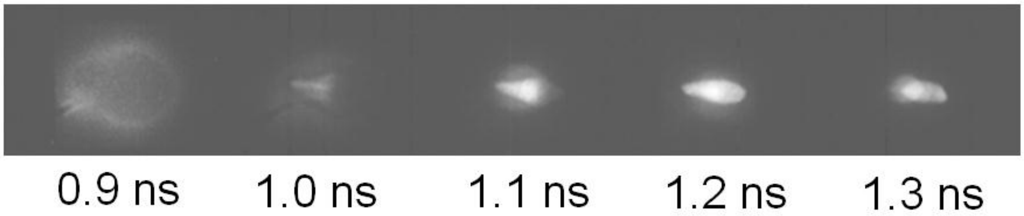

Figure 2 X-ray framing camera images of capsule implosion. An x-ray burst is created during the hot spot formation observed near 1.2 ns.

of 351 nm (3Ω) light was used to drive the shock wave. The target, shown in Figure 1, consists of an ablator, Ta single crystal, and VISAR window mounted on a heavymet pinhole. This target package is in turn mounted on the Broadband X-ray Diffraction (BBXRD) diagnostic, which is a heavymet pyramidal box with image plates.

For the high pressure experiments previously reported, a 10µm diamond ablator and a 1 ns laser pulse in the 10-45J energy range was used. Since 10J is near the lower limits achievable by the Omega facility, lower pressures were reached using a 3.7 ns pulse, which lowers the laser intensity, and by using a thick ablator (nominally 350µms) that allows the shock wave to attenuate as it propagates through the thickness.

The x-rays used to probe the lattice response of the tantalum are generated by an imploding capsule. The capsule, made of glow discharge plasma (GDP), is a 980µm diameter sphere with a 9µm wall with a vacuum center. The capsule is driven by 30-42 3Ω beams with 500J delivered in 1 ns. Figure 2 shows a series of x-ray framing camera images of the capsule implosion.
The capsule walls converge and create a 560 by 300 µm elliptical hotspot, ~ 1.2-1.4 ns after the lasers turn on. The timing of the capsule, crucial to determining the time history of the diffraction pattern, is confirmed with the DANTE diagnostic [5], which gives a signal proportional to the emitted power for several x-ray diode channels in the soft energy range. An example trace, shown in Figure 3, shows the capsule emits only faintly during the initially stage when the laser is on and puts out a burst of x-rays for approximately 200 ps. The emission spectrum during this x-ray burst, measured using a crystal spectrometer, is a broadband spectrum, extending up to the 25keV, with no significant emission lines [6].

For ease of implementation, the time at which the x-rays probe the shock compressed sample is controlled by varying the time of the target drive beam while keeping the capsule drive constant. Subsequently, the shock break out time, in addition to the shock pressure, is monitored by simultaneous VISAR measurements on each experiment. Previous high pressure experiments used a diamond VISAR window which was glued to the tantalum samples. To avoid the glue layer, which can degrade the quality of the VISAR signal, the current experiments utilized a MgO VISAR window.

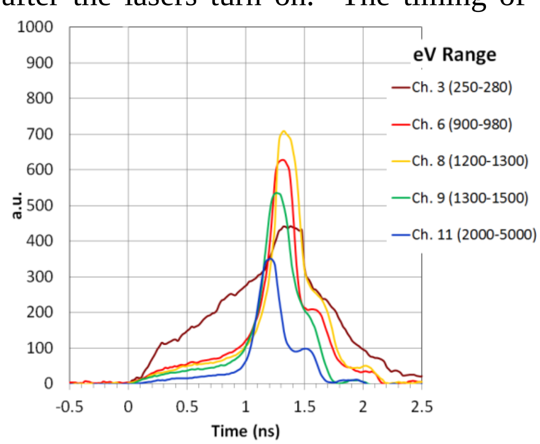

Figure 3 Dante traces of x-ray emission from capsule implosion. X-ray emission peaks at 1.2 ns.

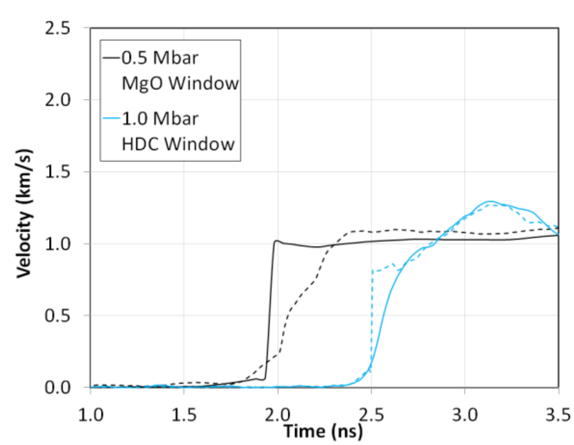

Figure 4 Example VISAR traces for 50 GPa experiments using an MgO window and 100 GPa using an diamond window.

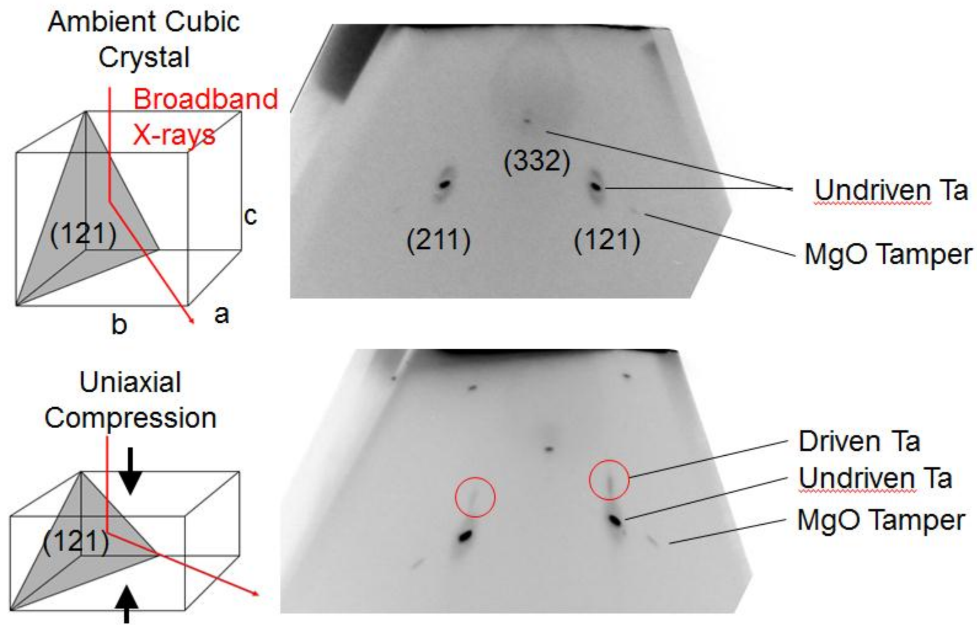

Figure 5 Laue diffraction patterns from image plates mounted on the BBXRD. (Top) Undriven diffraction spots with Ta indices marked. (Bottom) Driven diffraction signal with driven spots circled in red. (Left) Sketch of diffraction off of (121) plane during uniaxial compression.

Since the single-crystal samples were grown on a MgO substrate, a glue interface is fabricated by back-machining the MgO substrate down to a nominal 40µm thickness. Figure 4 shows an example VISAR traces for the low pressure setup at 50 GPa shock and the high pressure setup at 1 Mbar. The difference in shock impedance accounts for the higher pressure despite the similar interface velocities. In addition, it is worthwhile to note that high pressure target has a shock and then a steep ramp. This is

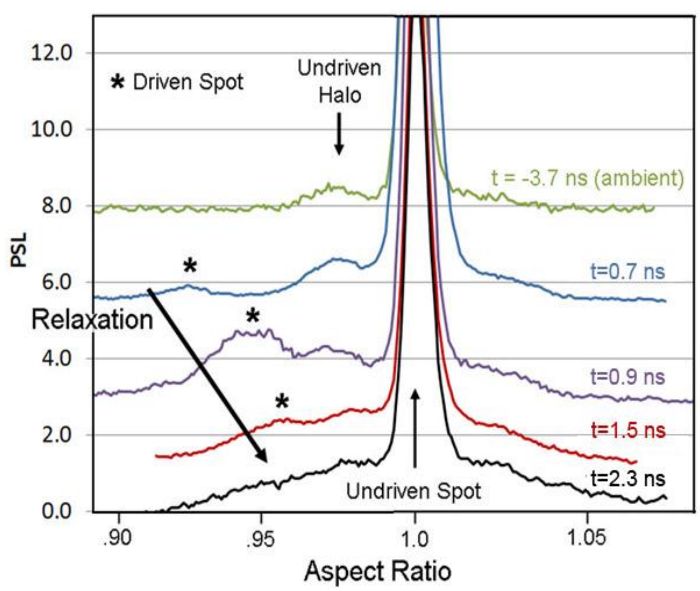

Figure 6 Lineouts from Laue images through both driven and undriven diffraction spots for a series of 50 GPa shock experiments

combination of the low impedance glue layer and the uneven laser pulse profile. Both problems are alleviated by using a thick GDP ablator: The GDP is nearly impedance matched to the glue and the large thickness provides enough time for the shock wave to even out any irregularities in the drive. The drawback of the thick ablator setup is the difficulty created in precisely controlling the relative timing of the drive and x-ray probe.

RESULTS

Diffracted x-rays are recorded on image plates held by the BBXRD, and examples of the Laue diffraction images are shown in Figure 5. An undriven (shock wave arrives after the x-ray probe) image is shown on top. The (211) family of planes are the brightest spots, with the (311) spot and spots corresponding to the MgO tamper also observable. In the driven image (bottom) the undriven spots are still observable since the x-ray probe occurs before shock breakout. In addition, driven spots corresponding to each (211) family spot are now observable, shifted “upward” towards

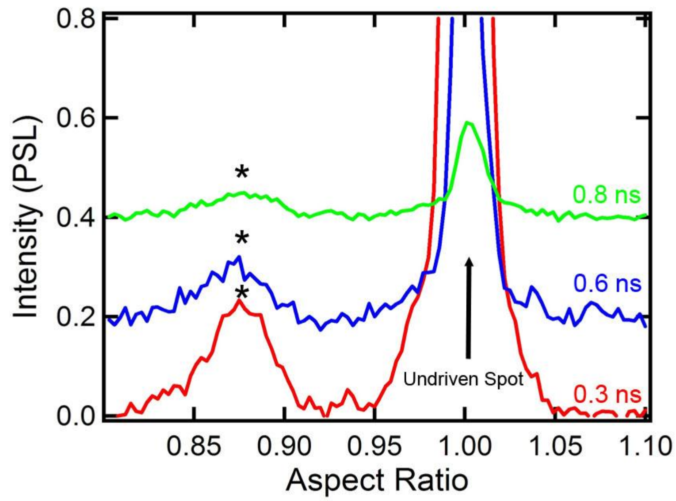

Figure 7 Lineouts through driven and undriven diffraction spots for a series of 100 GPa shock expeirments.

smaller Bragg angles. This shift is understood using a simple ray trace, as illustrated in Figure 5 (Left). As a unit cell of the tantalum is compressed, the orientation of the (121) plane changes, creating the upward shift. The shift of the Laue spots is therefore a function of the unit cell aspect ratio, *c/a*. Hydrostatic pressure, producing a volume change but no shape change, will not shift the diffraction spot. The shear strain and corresponding shear stress can be determined from the aspect ratio, as described by Comley et al. [4], with lower aspect ratios corresponding to higher shear strain.

A series of diffraction images were recorded with nominal pressure of 50 GPa, with time of the x-ray probe varying from

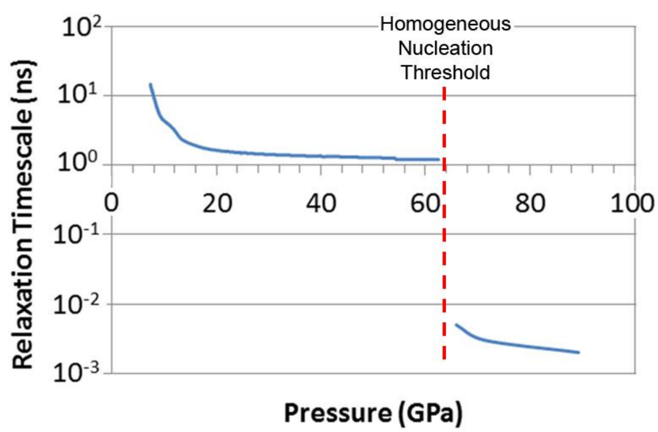

Figure 8 Multiscale model predictions of relaxation timescale following Rudd et al [7]

0.7 to 2.3 ns relative the shock wave entering the sample. The location of the driven diffraction spots changes with time, and lineouts, taken through the driven and undriven spots, are plotted in Figure 6 as a function of aspect ratio. High signal undriven spots are set to an aspect ratio of 1 and driven spots are located at aspect ratios less than 1 (compression). As time progresses, the driven spots move closer to the undriven spot, meaning the shear strain is decreasing with time. Over the course of 1 to 1.5 ns, the shear strain appears to approach a steady state.

A similar relaxation process is not observed at higher pressures. Figure 7 shows similar lineouts take from diffraction patterns for nominal shock pressures of 1 Mbar. The location of the driven spot does not change with time, indicating the material has relaxed on a time scale shorter than the first data point, ~0.3 ns.

DISCUSSION

The relaxation behavior in both the 0.5 and 1 Mbar cases is consistent with model predictions put forth by Rudd et al. [7]. The model holds that at 50 GPa, the material must first build up sufficent dislocations and then will relax to the yield surface over the course of ~1 ns. As the shock pressure increases, the material crosses the threshold for homogeneous nucleation of dislocations, allowing dislocations to nucleate throughout the material instead of multiplying from existing dislocations. Figure 8 shows predicted timescale for relaxation replotted on a lograthmic scale to show the above and below the threhold on the same plot. The homogeneous nucleation threshold is expected to occur at ~65 GPa, and above the threshold relaxation occurs over a few ps.

The aspect ratio measured from each experiment can be used to calculate the flow stress of the material, following Comley et al. [4]. For low pressure experiments, the material is assumed to be on the yield surface once two time points have similar shear stress. Time series were recorded for shock pressures at 25 and 50 GPa, and the corresponding relaxed shear stress is 4.4 and 5.8 GPa. These values are in line with those measured by lateral stress gauges [3]. Bourne et al. observed the shear strength increasing with applied longitudinal stress, and these values are plotted with the lowest shear stress found from Laue measurements for each data series at 25 and 50 GPa. Bourne et al. also observed the flow stress decreasing with time, but over the course of several microseconds. The maximum timescale of the Laue experiments is limited to 1-2 ns by the breakout of the shock wave. Delaying the breakout by making thicker samples is not feasiblt due to difficulties in growing larger single crystals and the attenuation of the x-ray signal that would result from transmission through a thicker Ta layer. It is possible that the shear stresses measured from Laue experiments will continue to relax if observed on timescales much longer than the 1-2 ns timescale of the experiments

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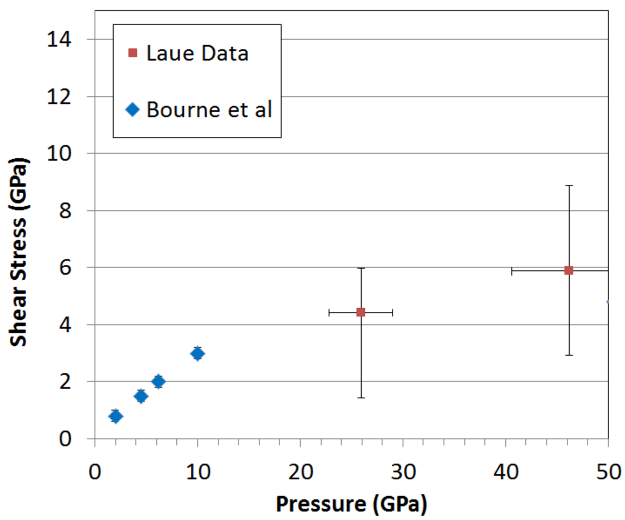

Figure 9 Comparison of measured flow stress using lateral stress gauges [3] and Laue data (this work).

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