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

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Abstract. Laser driven shock experiments were performed at the Omega facility to study the dynamic yield strength of $\sim 5$ $\mu$m thick single crystal tantalum using in-situ Laue diffraction. Tantalum samples were shocked along the [001] direction to peak stresses up to 50 GPa and probed using a 150 ps pulse of bremsstrahlung radiation from an imploding CH capsule x-ray source timed for when the shock was halfway through the sample. The capsule implosion was monitored by a combination of pinhole cameras and DANTE x-ray diode scopes. Diffraction spots for both the undriven and driven regions of the sample were recorded simultaneously on image plate detectors. The strain state of the material was found by combining the strain anisotropy found from the driven diffraction pattern and with simultaneous VISAR measurements.

1. 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 a 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, provide 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 direct measurement of the strain anisotropy, the difference between the strain in the shock and lateral directions, in single-crystal materials under laser-driven shock using in-situ Laue x-ray diffraction [4]. Previous work examined shocks in the 60 to 180 GPa range. This work reports the results of additional experiments using a modified experimental setup that extends the in-situ Laue experiments to the 25 to 50 GPa range. Experimental details from both setups will be compared.
2. Methods

The \textit{in-situ} Laue shock experiments were performed at the Laboratory for Laser Energetics Omega Facility. A single beam of 351 nm wavelength (3\(\omega\)) light was used to drive the shock wave. The target, shown in figure 1, consists of a plastic (CH) ablator, Ta single crystal, and an MgO 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 [4], a 10 \(\mu\)m diamond ablator and a 1 ns laser pulse in the 10-45 J energy range were used [4]. Since 10 J is near the lower limits achievable by the Omega facility, a modified setup was developed to reach shock pressures down to 25 GPa. The lower pressure setup used 3.7 ns pulse, which lowers the laser intensity, and a thick ablator (nominally 350 \(\mu\)m) 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 polymer (GDP), is a 980 \(\mu\)m diameter sphere with a 9 \(\mu\)m wall with a vacuum fill. The capsule is driven by 29-42 beams of 3\(\omega\) light with 500 J/beam delivered in 1 ns. Figure 2 shows a series of x-ray framing camera images of the capsule implosion. 1.2-1.4 ns after the laser turns on, the capsule wall converges and creates a 560 by
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 mostly soft x-rays during the initial stage when the laser is on and then puts out a burst of broadband x-rays lasting approximately 200 ps. The x-ray burst is assumed to occur at the average time of peak emission for all channels, 1.3 +/- 0.1 ns.

Figure 4 shows the time-integrated spectrum measured using a dual crystal spectrometer (DCS) for capsule implosions driven by 42 and 29 beams. We use 42 beams for the high-pressure setup, while restrictions associated with using a different pulse length for the capsule and Ta sample drives limits the low pressure drive to 29 beams. The DCS measurements were calibrated against published data using a similar experimental setup [6]. Both curves show the capsule emits a broadband spectrum without significant emission lines. The efficiency of the two capsule drives are approximately equal (within shot to shot variation) up to 18 keV, at which point the 29 beam drive begins to drop off.

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 tamper that was glued to the tantalum sample. To avoid the glue layer on the tamper, which can degrade the quality of the VISAR signal, the current experiments utilized an MgO VISAR window. Since the single-crystal Ta samples were grown on an MgO substrate, a glueless tamper (VISAR window) is fabricated by back-machining the MgO substrate down to a nominal 40 µm thickness.

Figure 5 shows example VISAR traces for 50 GPa and 130 GPa shock strengths. The solid and dashed curves represent two legs of the VISAR system with different etalon thicknesses, with the solid lines representing the leg with the smaller etalon delay. The 3.7 ns laser pulse used for the 50 GPa drive (labeled Drive (A) in figure 5) is set to turn on 40-42 ns before the capsule drive, so that the x-ray probe will occur during the shock wave transit through the Ta sample.
Figure 5. (Color Online) Example VISAR traces for (black) 50 GPa experiments using a thick CH ablator and MgO window and (blue) 130 GPa using a diamond window. The shock and ramp character of the high pressure drive is due to the impedance mismatch with surrounding glue layers and uneven laser pulse.

It is worthwhile to note that the 130 GPa high-pressure target has a shock and then a steep ramp. This results from the combination of the low impedance glue layers and the uneven laser pulse profile. Both problems are alleviated by using a thick GDP ablator and the MgO tamper. The GDP is nearly impedance matched to the glue on the ablator, and the large thickness provides enough time for the shock wave to even out any irregularities in the drive. Since the Ta crystal is grown on the MgO, there is no glue layer at the Ta-tamper interface. The drawback of the thick ablator setup is the difficulty created in precisely controlling the relative timing of the drive and x-ray probe.

3. Results and Discussion

Diffracted x-rays are recorded on image plates held by the BBXRD, and examples of the Laue diffraction images are shown in figure 6 for a 50 GPa shock moving in the [001] direction. An undriven image is shown on top. The spots from the \{121\} family of planes are the brightest, with the (332) 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 both \{121\} family lattice planes are now observable, shifted “upward” towards smaller Bragg angles.

The shift in the driven spots is understood using a simple ray trace analysis, as illustrated in figure 6 (Left). As a unit cell of the tantalum is shock compressed along the [001] direction, 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 change the diffracted wavelength but will not shift the Laue spot location in this configuration, since the orientation of the lattice plane relative to the incident x-rays is unchanged. The strain anisotropy 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.

The shear stress was previously reported [4] by determining the longitudinal stress (along the
Figure 6. (Color Online) (Left) Sketch of x-rays incident along the [001] direction diffracting off of the (121) plane under ambient conditions and uniaxial compression due to shock loading along the [001] direction. (Right) Laue diffraction patterns from image plates mounted on the BBXRD with broadband x-rays incident along the [001] direction of a Ta single crystal. (Top) Undriven diffraction spots with crystal indices marked. (Bottom) Driven diffraction signal for 50 GPa shock pressure with driven spots circled in red.

shock propagation direction) from impedance matching using VISAR and the ablation pressure reported by Fratanduono et al. [7]. At the time of that publication, no data were available for the VISAR correction factor for a diamond window, thus an estimate of 2.7 was made based on diamond anvil cell data. New data from laser-driven ramp-compression experiments performed at the National Ignition Facility estimates the correction factor at 2.0, although additional analysis is needed to confirm this [8]. Using this correction factor moves the longitudinal stress to higher values, but also produces better agreement with the diamond ablation pressure and VISAR data using MgO windows and the recently published MgO correction factor of 1.78 [9]. Using the new correction shifts the measured pressure to higher values. For example, the high-pressure VISAR trace shown in figure 5 shift from 100 to 130 GPa. In general, the measured shear stress will shift to higher values also, since the elastic constants increase with pressure, but the higher shear stresses are typically within the error bars of the original values. Using this new diamond window correction, the Livermore Multiscale strength model still agrees with the diffraction data within their error bars up to about $P_{\text{shock}} \sim 100$ GPa. The disagreement with the data above 100 GPa, however, is slightly larger. This discrepancy will be addressed in future work.

In many cases, multiple experiments were performed at similar pressures. Data taken at the latest time relative to the shock wave entering the sample are assumed to be essentially in the 3D relaxed lattice state. For the 50 GPa and 130 GPa shock drives shown in figure 5, we measured flow stresses of 6 +/- 2 GPa and 17 +/- 3 GPa respectively. The lowest pressure shock experiments were performed at 27 GPa, which is approaching the regime studied in gas-gun experiments. At 27 GPa, we measured a flow stress of 4 +/- 2 GPa, significantly higher than the 1.3 GPa peak shear stress found by Reed et al. [1] at similar pressures; however, Reed et al. note that the strength of the material will be highly path dependent, making direct comparison difficult. It is possible that the very small sample thicknesses used here (5 µm) compared with
those used in gas guns (1-2 mm) means that the strain rate may be significantly higher for the present work, leading to a higher strength.

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