

Laser compression of monocrystalline tantalum

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Abstract

Monocrystalline tantalum with orientations [100] and [111] was subjected to laser-driven compression at energies of 350–684 J, generating shock amplitudes varying from 10 to 110 GPa. A stagnating reservoir driven by a laser beam with a spot radius of $\sim 800\ \mu\text{m}$ created a crater of significant depth (~ 80 to $\sim 200\ \mu\text{m}$) on the drive side of the Ta sample. The defects generated by the laser pulse were characterized by transmission and scanning electron microscopy, and are composed of dislocations at low pressures, and mechanical twins and a displacive phase transformation at higher pressures. The defect substructure is a function of distance from the energy deposition surface and correlates directly with the pressure. Directly under the bottom of the crater is an isentropic layer, approximately $40\ \mu\text{m}$ thick, which shows few deformation markings. Lattice rotation was observed immediately beneath this layer. Further below this regime, a high density of twins and dislocations was observed. As the shock amplitude decayed to below ~ 40 GPa, the incidence of twinning decreased dramatically, suggesting a critical threshold pressure. The twinning planes were primarily {112}, although some {123} twins were also observed. Body-centered cubic to hexagonal close-packed pressure induced-transformation was observed at high pressures (~ 68 GPa).

The experimentally measured dislocation densities and threshold stress for twinning are compared with predictions using analyses based on the constitutive response, and the similarities and differences are discussed in terms of the mechanisms of defect generation. © 2012 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

Keywords: Dislocation; Laser treatment; Tantalum; Twinning; Shock compression

1. Introduction

Although the first laser shock experiments, by Askaryan et al. [1], date from the 1960s, and early work showed the potential use of laser shock pulses to harden aluminum alloys [2,3], there has been only limited inquiry on the nature of laser-shock-induced defects. White [4,5] and others [6–8] introduced the use of lasers to obtain Hugoniot data over a broad range of pressures.

A systematic inquiry into the effects of laser pulses on fcc metals (Cu and Cu–Al) was initiated in 2001 and has yielded significant results that have been explained in terms

of shock compression [9–11]. This work was extended to nickel by Jarmakani et al. [12].

The objective of this study is to extend the methodology developed for copper and nickel to a model body-centered cubic (bcc) metal, tantalum. There are important fundamental differences between face-centered cubic (fcc) and bcc metals; in tantalum, the Peierls–Nabarro stress is ~ 2.97 GPa [13], whereas it is only ~ 19 MPa in copper [14]. This difference profoundly affects the temperature and strain-rate sensitivities, and is expressed in different constitutive equations developed by Zerilli and Armstrong [15]. Tantalum has been subjected to shock compression experiments using gas-gun [16] and explosively driven flyer plate techniques [17]. The slip–twinning transition has been observed [18,19], and the bcc–hexagonal close-packed

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(hcp) transformation was identified by Hsiung [20] and Hsiung and Lassila [21,22].

The dislocation response is governed at low strain rates by thermal activation. With increasing strain rate, drag (phonon and electron) mechanisms become relevant [23], as well as a proposed new regime of effective “drag” through debris generation [24]. At even higher strain rates, relativistic effects have been postulated.

In spite of extensive research, we still do not fully understand at the lattice level how a strong shock – that is, a shock where the plastic wave has a higher shock velocity than the elastic precursor – propagates through a solid sample [9]. Further, the timescale and physical processes involved in elastic–plastic [25] and polymorphic phase transitions [26] are fertile areas of investigation.

The regimes obtained by laser-induced compression are extreme and cannot be accessed by other experimental methods. The timescales are two to three orders of magnitude shorter than those in gas-gun and explosive experiments. The goal of this research is to probe the mechanisms of plastic deformation (slip and twinning) in a time and pressure region accessible via laser energy deposition. Recovery experiments of ramp-loaded, monocrystalline Ta were designed to study mechanisms of plastic deformation and failure at high pressure and strain rates.

2. Experimental techniques

Pure monocrystalline Ta was obtained from MarkeTech Intl, Inc. in cylindrical shape, with dimensions of 3 mm diameter and 3 mm height. The interstitial impurities (ppm in weight) in Ta measured by the Evans Analytical Group are O:<10, N:<10, H: 7.6 and C:<10. The laser recovery experiments were performed at the Laboratory for Laser Energetics, University of Rochester (Omega Facility). The experimental set-up, shown in Fig. 1, had previously been tested for recovery of fcc metals [9]. The cylindrical tantalum monocrystal targets were placed behind a tantalum washer inside a stainless steel recovery container. The inside of this container was filled with silica aerogel, which acted as a deceleration medium for the tantalum specimens after they had undergone compression loading.

The recovery container was designed to be mounted in the Omega chamber [27,28] (Fig. 1a). Fig. 1b shows a more detailed view of the recovery set-up. A shock was driven into the 180 μm BrCH (2%) reservoir via direct illumination of the 20 μm polycarbonate ablator by six overlapping beams at a nominal energy of ~ 60 J per beam for ~ 3 ns. The standard SG8 distributed phase plates (focal spot of radius ~ 400 μm) were used [29] on each beam, with best focus at the ablation surface. The overlap region between the six beams was optimized to ensure a large, uniform ablation front. The stagnation of the reservoir material against the Ta sample provided a quasi-isentropic loading profile for a few tens of micrometers of Ta sample before steepening into a shock [30]. The detailed cross-section of

the target holder with the tantalum specimen to be studied is shown in Fig. 1c. The specimens were successfully recovered in this geometry. The aerogel did not introduce any additional damage into the recovered samples and acted as a gradual decelerating medium. A removable cap with a centered 4 mm hole was used to clamp and fix the sample at the front end of the tube (Fig. 1a).

The generation of shockless compression using an expanding plasma has three stages. First, the incident laser energy flux is converted in the ablator/reservoir into a low-density plasma [27]. Secondly, the plasma expands in the gap. Thirdly, the plasma stagnates and piles up against the front surface of the tantalum, producing a monotonically rising pressure. The amplitude of the pressure wave propagating into the monocrystal increases and gradually steepens into a shock wave as it propagates into the metal. Surface heating effects are minimized through this process. A 3 mm diameter and 20 μm thick polycarbonate ablator ($\text{C}_{16}\text{H}_{16}\text{O}_4$), density 1.2 g cm^{-3} , followed by 180 μm thick brominated polystyrene reservoir ($\text{C}_{50}\text{H}_{48}\text{Br}_2$), density 1.23 g cm^{-3} , was placed on the laser-irradiating front surface of the tantalum washer (Fig. 1c). The Ta washer, with a machined radial groove for vacuum pumping of the gap (marked in Fig. 1c), was clamped between the cap and the front end of the tube. The radial groove was designed for pumping out the gap between the ablator/reservoir and the front surface of monocrystals. The internal diameter of the Ta washer is 2 mm, determining the diameter of the compression pulse.

Five recovery experiments on monocrystals and three complementary VISAR (Velocity Interferometer System for Any Reflector) experiments of the drive were performed. The VISAR experiments were conducted on Al–LiF drive calibration samples and provided interface velocity data that allowed the pressure vs. time of loading to be deduced, which became the input to the subsequent computer simulations. The total drive laser energies (E_{Laser}) varied between 350 and 684 J.

The shocked targets were examined using a profilometer, a microhardness tester, a scanning electron microscope (Phillips XL30 ESEM) and transmission electron microscopes (operated at 200 kV). Transmission electron microscopy (TEM) foils were prepared by electropolishing and focused ion beam (FIB; Hitachi NB-5000 FIB-SEM) techniques. The electropolishing liquid was a solution of 87.5 vol.% methanol, 10 vol.% sulfuric acid and 2.5 vol.% hydrofluoric acid, which was used to polish at ~ 25 V and ~ -35 °C. The temperature was lowered by pouring liquid nitrogen directly into the electropolishing solution. FIB samples were prepared by cutting targets into half along the energy deposition direction and mounting them into epoxy. They were mechanically polished down to 0.05 μm using Al_2O_3 and coated with a thin layer of Ir before the FIB milling procedure. The FIB samples were perpendicular to the shock propagation direction and had thicknesses of 50–100 nm. DIFFRACT[™] was used to simulate the diffraction patterns taken from TEM images.

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