

Dynamic strength of tantalum under impact

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Abstract. Two sets of plane impact experiments were carried out on tantalum targets (1-2 mm thick): shock re-shock and shock-rarefaction. Some of the experiments were with and some without a LiF window. VISAR diagnostics was used to measure free surface velocity or particle velocity. The VISAR information was utilized to study the equation of state and dynamic strength of tantalum under compression and tension. The Hugoniot pressures in the experiments were roughly 6, 13, and 34 GPa. Coupling between 1d hydrodynamic simulation and a calibrated Zerilli-Armstrong model reproduces the experimental results fairly well. Spall strength extracted from pull back velocity yields a relatively high value of 6.3-6.5 GPa with negligible pressure dependence.

1. Introduction

We have previously utilized shock rarefaction/re-shock experiments, in the spirit of the Asay self-consistent technique [1], to study strength of face centered samples (FCC), in particular SS304-L [2]. This metal is expected to show strength properties that are mildly dependent on strain rate (SR) or over-relaxation effects of the yield surface (OREYS). However, SS304L clearly shows strain rate dependence via the Johnson-Cook model.

Here, we extend our material strength experimental study to the body centered cubic (BCC) metal tantalum (Ta), a material with complicated mechanical properties. BCC metals, particularly Ta, exhibit a high temperature and SR sensitivity [3], or OREYS depending on one's preferred interpretation [4]. By now, it is well established that the mechanical properties of Ta are strongly affected by the production procedure and the presence of impurity atoms [3]. Moreover, line VISAR measurements demonstrated that spall strength and Hugoniot elastic limit (HEL) show significant statistical variability even on the same sample [5]. Recent work [6-9] has demonstrated that isentropic elastic limit (IEL) is of the same order of magnitude as the HEL, and there is elastic precursor decay as a function of the sample thickness. Yet, in spite of nearly two decades of intensive experimental and theoretical research, the details of the underlying deformation mechanism of Ta remains poorly understood. Nonetheless, it clear that the various phenomena associated with the Ta ($\alpha \rightarrow \omega$ phase transition, the formation of twins, and material strength) are dominated by collective dislocation phenomena [10, 11].

These Ta-related phenomena have been addressed theoretically over a wide range of pressures [12]. Among the proposed mesoscale mechanisms are homogenous dislocation generation and dislocation multiplication. From molecular dynamic simulations, homogenous nucleation of dislocations is expected to occur above 62 GPa [5]. Thus, it seems that for the range of experiments reported here [5-9,13] only dislocation multiplication and twinning might be relevant (but see [14] for the opposite



interpretation). In any case, the approach taken here is a macroscopic one, and the use of constitutive macroscopic models (which do and do not take into account dislocation multiplication and twinning) to the experimental results is attempted.

This paper addresses the experimental setup in section 2, the experimental results in section 3. Theoretical, 1D plastodynamic simulation including common strength models and the equation of state (EOS), and comparison between the models and the VISAR histories are discussed in section 4. We end in section 5 with a short discussion and our current conclusions.

2. Experimental Setup

The experimental setup is shown in figure 1.

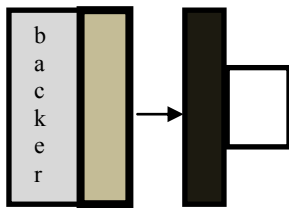


Figure 1. The experimental setup consists of a composite of a tantalum target (black) and LiF or vacuum anvil, and a composite projectile in which the first layer is aluminium and the backer is either tantalum or lexan.

This setup, in the spirit of the Asay Self-consistent technique [1], was previously used with sapphire anvils and tantalum targets [13]. A VISAR diagnostic was used to measure the mass velocity profile of each experiment. The experiments reported in this paper are presented in table 1. They are divided to two main groups: with and without a LiF anvil. In all the experiments the shock wave is not overridden and one can extract significant information from the elastic precursor properties. The shots with the LiF anvil were performed in order to provide information on the pressure dependence of the constitutive model. The anvil release/unloading experiments provide information with regard to the spall strength of Ta. Commercially pure (99.90%) tantalum plates, 1mm and 2 mm thick were used in this study. The average grain size of the tantalum is 120 μm .

Table 1. Experimental data.

Exp #	Impactor Type, thickness (mm)	Impactor velocity (km/s)	Anvil (type)	Target thickness (mm)	U_s (km/s)	P_H (GPa)	σ_{HEL} (GPa)
Ta2506	Ta (1)	0.462	None	2	3.54	13.6	2.23
Ta4065	Al (1.55), Ta (2)	2.167	None	2	4.01	34.0	2.94
Ta4066	Al (2)	2.162	None	2	3.99	33.9	3.26
Ta4071	Al (2), Ta (2)	2.197	None	2	3.98	34.6	2.76
Ta2507	Al (0.53), Ta (2)	0.497	LiF	1	3.36	6.2	1.93
Ta2508	Al (0.5)	0.493	LiF	1	3.45	6.1	2.72
Ta2510	Al (0.52), Ta (2)	0.483	LiF	1	3.27	6.0	1.97
Ta2511	Al (1), Ta (2)	0.871	LiF	2	3.56	11.4	2.72
Ta2512	Al (1)	0.982	LiF	2	3.61	13.1	2.85

3. Results

The experimental setup parameters and part of the results are summarized in table 1. Since all the experiments show an elastic precursor, we can extract the plastic wave velocity from the VISAR measurements using the relation:

$$U_s = h \cdot \left(\frac{h}{c_l} + \Delta t \right)^{-1} \quad (1)$$

Under the reasonable assumption that for the low pressure range considered here, the longitudinal sound speed is pressure independent. h is the Ta target thickness, c_l (4.25 km/s) is the longitudinal sound velocity measured by an ultrasonic technique and Δt is the time difference between the arrival time of the elastic precursor and the plastic wave arrival time (as can be seen in figures 2 and 4). The waves' arrival time is taken in the middle of their rise time. This analysis shows that at low pressure the shock velocity is lower than the one calculated based on the linear relation between the shock and particle velocities, U_s and U_p , respectively, given by Marsh [15]. Similar results were also obtained in [6]. In the low pressure range we find that the relation $U_s = 3.15 + 1.65U_p$ fits the experiments more adequately. The Hugoniot pressure given in table 1 was calculated by $P_H = \rho_0 U_s U_p$, where ρ_0 is the density of unshocked sample (16.65 g/cc).

3.1. Experiments with LIF anvils

A typical VISAR history of a shot with a LiF window is shown in figure 2. We note that in all reshock experiments, a minor release wave is observed prior to the second shock signal as shown in figure 3. At the moment it is not clear if this is a result of a physical feature or an experimental artefact that is related to the projectile properties, i.e., from a thin glue layer between the Al first layer and the Ta second layer of the impactor.

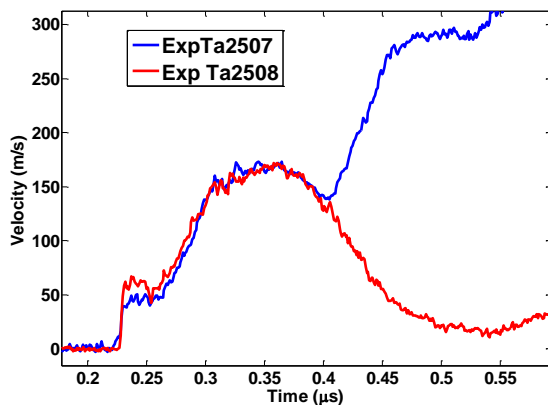


Figure 2. VISAR histories of a shock reshock experiment with a LiF anvil.

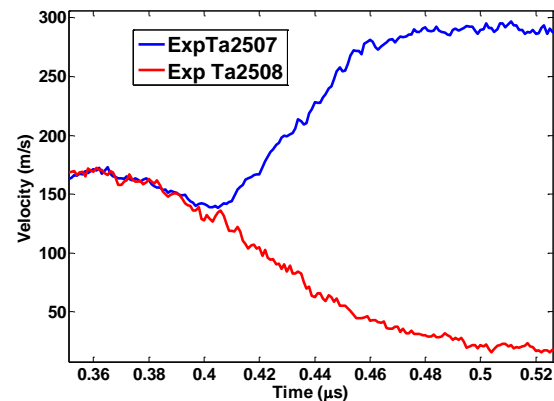


Figure 3. Zoom on the region of release and reshock experiments of a 1 mm target.

3.2. Experiments without anvils

VISAR signals of windowless experiments are shown in figure 4. The spall strength was calculated from the pull back velocity measured in experiment Ta2506 (at $P_H = 13.6$ GPa) and experiment Ta4066 (at $P_H = 33.9$ GPa) according to [16]. It was found that the spall strength is relatively high, 6.3-6.5 GPa, with negligible pressure dependence. The spall strain rate in both cases was $\sim 2 \times 10^5 \text{ s}^{-1}$.

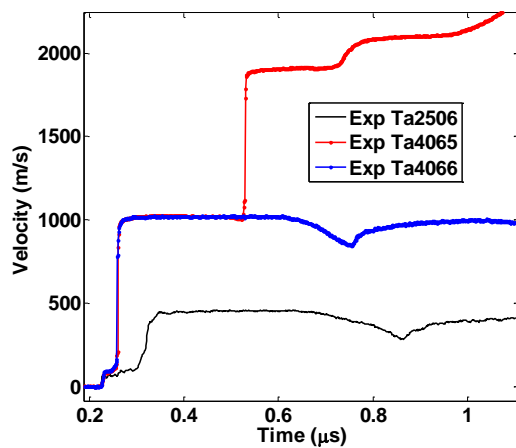


Figure 4. VISAR histories of the anvil-less experiments.

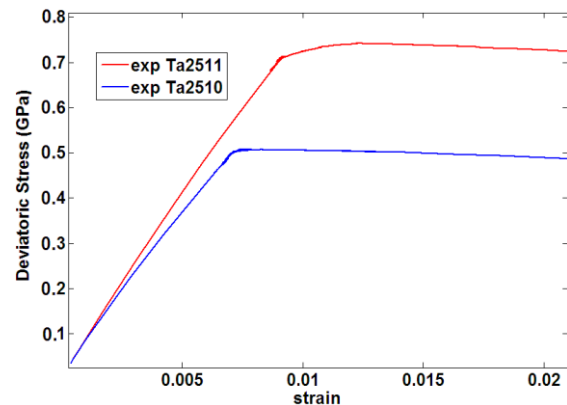


Figure 5. Deviatoric stress as function of strain for Ta. Calculated from the VISAR measurements.

3.3. HEL Results

The Hugoniot elastic limit (HEL) stress can be calculated by:

$$\sigma_{HEL} = \rho_0 c_l u_{HEL} \quad (2)$$

where u_{HEL} is the particle velocity calculated from the surface velocity at the elastic-plastic transition (determined at the first break in the velocity profile). All the experiments provided at high Hugoniot pressure show a rather high value of the elastic precursor speed from which the so-called Hugoniot elastic limit can be extracted, probably due to uncompleted relaxation of the elastic precursor decay. At lower Hugoniot pressures, the elastic precursor results are in a good agreement with [6-8]. In general, at higher Hugoniot pressure the HEL is higher. At lower pressures the HEL decay is rather small [6,8]; therefore the error involved with extracting deviatoric stress and appropriate strain from the VISAR measurements is reasonable. Our results do not show significant elastic precursor decay, allowing us to get a stress-strain relation for mild strains. Deviatoric stress as a function of strain for Ta is shown in figure 5 for two experiments: Ta2510 at $P_H = 6$ GPa and Ta2511 at $P_H = 11.4$ GPa. In both cases no hardening effects are demonstrated.

4. Theoretical consideration

Although precursor decay effects cannot be accounted for without an explicit or implicit overstress method [5-8], the overall performance of the standard explicitly strain rate-dependent models is rather good (cf. [5]). Therefore, we have carried out numerical simulations using the Zerilli-Armstrong (ZA) model. We note that standard split Kolsky-Hopkinson bar calibration [17] of the ZA model is inadequate for impact-like experiments [4], and a recalibration is required. We have also taken an approach of getting the best fit to one particular shot from the shot ensemble given in table 1. Then we used the same parameters for all shots. Figure 6 shows our attempt to use this model to fit the middle velocity range of our experiments. Attempts to use the Johnson-Cook (JC) model are known to reproduce the plastic wave viscous nature, but fail in the reproduction of the elastic wave [4,5]. Our calculation yielded similar results (not shown here due to page limit). The ZA model is given by:

$$y = C_o + C_5 (\varepsilon_p)^n + C_1 \exp[-C_3 T + C_4 T \ln(\dot{\varepsilon}_p)] \quad (3)$$

where we have kept the nomenclature of [4]; T is the temperature, ε_p is the plastic strain, and $\dot{\varepsilon}_p$ is the plastic strain rate. The values of the constants we used are given in table 2. We have also attempted to use the JC and ZA calibration provided in [4]. This yields a very viscous-like VISAR profile that did not fit the experiments at all.

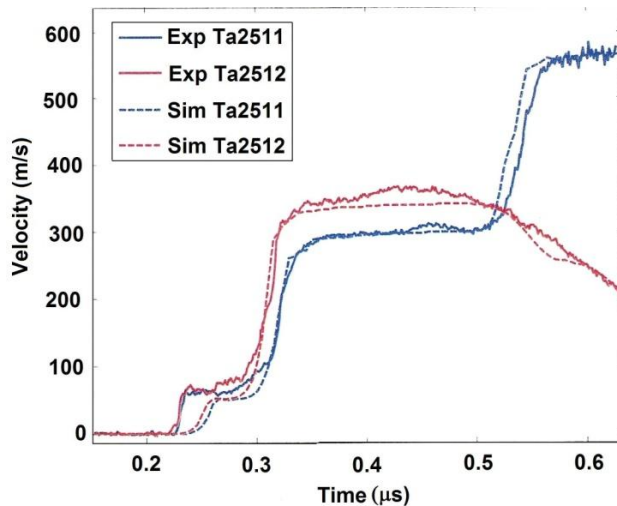


Table 2. Material constants for tantalum used in ZA model.

Constant	Value
C_0 (GPa)	0.9073
C_1 (GPa)	1.303
C_3 (K ⁻¹)	0.0076
C_4 (K ⁻¹ s ⁻¹)	0.00053
C_5 (GPa)	0.465
n	0.5

Figure 6. VISAR histories of a shock reshock experiment with a LiF anvil (exp. Ta2511, Ta2512) and simulation using recalibrated ZA model.

5. Conclusions and Discussion

We have carried out plane impact experiments on Ta in the spirit of Asay self-consistent technique (Asay analysis procedure does not simply apply for strain rate-dependent materials). The fact that the shock waves were not overridden provides a wealth of additional information on the constitutive model. Matching the experimental results revealed a deviation from the equation of state for Ta given by Marsh [15] at low Hugoniot pressures. Our ZA model calibration for the shock regime differs significantly from that of [17]. However, it also differs from the best calibration provided in [4]. In light of the variability of Ta strength properties, which are dependent on the chemical composition, manufacturing procedure, and the post-treatment of the as received material, this is not particularly surprising. Our results are in agreement with previous experimental work that shows a relatively high resistance of Ta to spall.

No elastic precursor decay was observed in the lower range, in contrast to previous work. We suspect that this is a result of the fact that most of the experiments presented in the literature use higher impedance.

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