

Non Shock Dynamic Compression of Tantalum

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ABSTRACT

We start by simulating the response of tantalum to dynamic non-shock loading using a standard hydrocode, and the results we get are not consistent with test data. Standard hydrocodes use what we call the flowstress approach to describe the dynamic viscoplastic response of materials. We therefore transform our hydrocode to use what we call the overstress approach to dynamic viscoplastic response. It turns out that using the overstress approach makes the hydrocode more successful in reproducing non-shock dynamic compression test data.

INTRODUCTION

In recent years we see more reports on gradual (non-shock) dynamic loading of various metals to high pressure [1,2]. The advantage of gradual dynamic loading over shock loading is: 1) it's possible to control the loading rate independently of pressure. This is important as strength increases considerably at very high strain rates [3]; 2) When a material undergoes an isentropic loading path (not a shock), it heats up at a slower rate than from a shock (there is no shock heating). It's therefore possible to determine the influence of pressure on strength separately from the influence of temperature.

In Fig. 1, taken from [1], we see the response of tantalum targets to non-shock loading at uniaxial strain (plane strain loading), where pressure is under 20GPa.

We see from Fig. 1 that details of the initial response depend on the initial state of the tested material. Tantalum samples in tests designated (a) went through an annealing process, and contain a relatively small number of defects and dislocations. The elastic wave in these samples has an initial spike which then connects smoothly to the plastic part of the signal. On the other hand, tantalum samples in tests designated (b) went through a cold-rolled process, and therefore contain a large number of dislocations. There is no elastic spike in the response signals of these tests. Instead, the rise to the elastic wave is gradual, and so is the initial rise from the elastic wave to the plastic wave. Trying to reproduce the results of Fig. 1 using a hydrocode that contains a regular strength model yields inaccurate results.

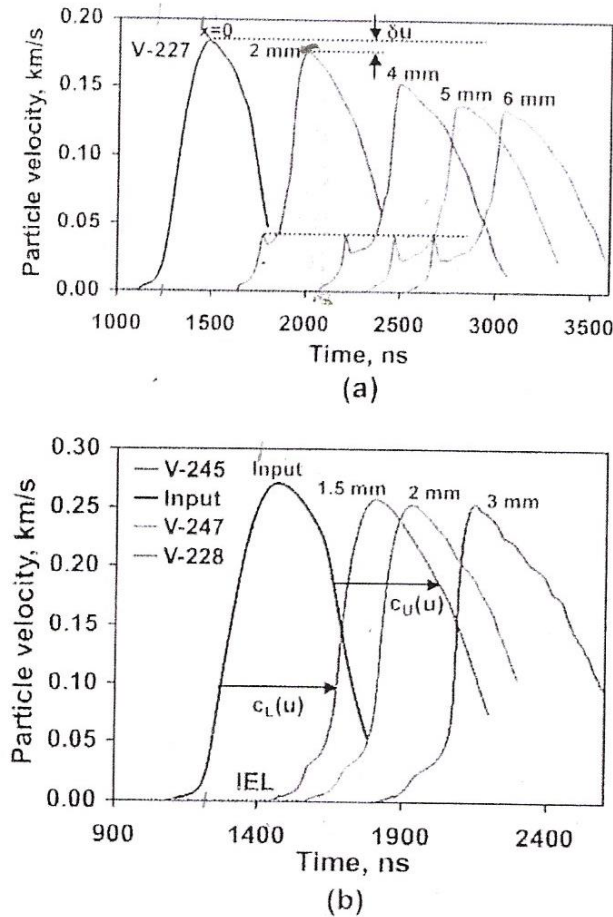


Figure 1. Copied from [1]. Particle velocity histories at different depths into the target. (a) annealed tantalum. (b) cold-rolled tantalum.

In Fig. 2 we show an example of such a simulation: 1) we use a Mie-Gruneisen EOS [4] with constant $\rho\Gamma$ and with Steinberg's parameters [5]; 2) we use an initial strength of $Y_0=0.77\text{GPa}$ and an initial shear modulus of $G_0=69\text{GPa}$; 3) we change strength and shear modulus with pressure and temperature according to [6]:

$$\frac{Y}{Y_0} = \frac{G}{G_0} = \frac{K}{K_0} = \frac{\rho c^2}{\rho_0 c_0^2} \quad (1)$$

Where K =bulk modulus, ρ =density and c =sound speed; 4) there are no strain hardening or strain rate hardening; 5) the boundary particle velocity rises at a constant rate during $0.25\mu\text{s}$ and stays there. Also, as mentioned above, we use the regular strength model included in standard hydrocodes. We refer to such models as flowstress approach strength models [7].

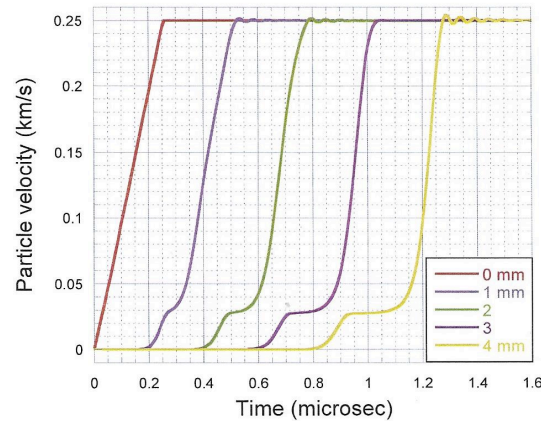


Figure 2. Particle velocity histories every 1mm, from constant velocity rate loading of the boundary, using the standard flowstress approach with radial return according to Wilkins [8].

We see from Fig. 2 that as expected, a constant level elastic precursor wave is formed. The elastic precursor wave then gradually joins the plastic wave in a way that has no resemblance to the curves of Fig. 1. In what follows later we use what we call the overstress approach to dynamic plasticity [7] to reproduce the same tests as above. As strain rate hardening is an integral part of the overstress approach, we first apply in what follows next the same amount of strain rate hardening to simulations with the flowstress approach. We do this mainly for comparison purposes. With the overstress approach the effective deformation rate is given by:

$$d_{\text{eff}}^p = A \left(\frac{\sigma_{\text{eq}} - Y_{\text{qs}}}{Y_0} \right)^\alpha \quad (2)$$

But with the flowstress approach, the equivalent stress is the flow stress. We therefore get:

$$Y = \sigma_{\text{eq}} = Y_{\text{qs}} \left[1 + \frac{Y_0}{Y_{\text{qs}}} \left(\frac{d_{\text{eff}}^p}{A} \right)^{1/\alpha} \right] \quad (3)$$

We repeat the simulations of Fig. 2, but with strain rate hardening according to Eq. (3). We use $A=0.1/\mu\text{s}$ and $\alpha=2.4$. We show the results in Fig. 3.

We see from Fig 3 that what strain rate hardening does is: 1) it increases the elastic precursor wave level, and 2) it does not reproduce a waveform that is similar to the test results (Fig. 1). In what follows later we perform similar simulations using the overstress approach.

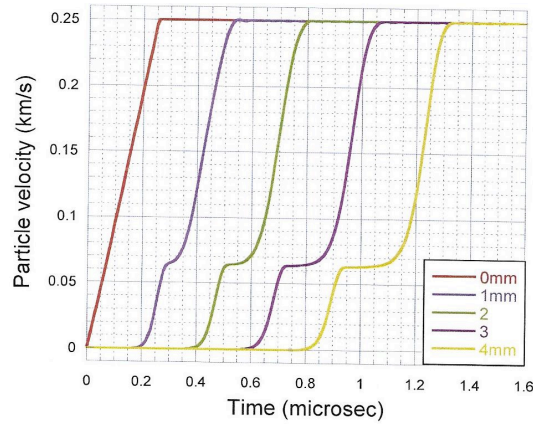


Figure 3. Particle velocity histories from constant velocity rate loading on the boundary. The computation uses the flowstress approach with a strain rate hardening similar to the one used later with the overstress approach

INSERTING THE OVERSTRESS APPROACH INTO OUR HYDROCODE

We introduce the overstress approach into a standard and old code that we use (PISCES2D) for the case of uniaxial symmetry. We perform the needed changes through the user subroutine EXYLD that evaluates the flowstress. We enter this subroutine for every computational cell and for each time step. Entering the subroutine, we know the values of the following variables: 1) components of the total deformation rate d_{ij} , from which we compute the components of its deviator δ_{ij} in the usual way; 2) components of the stress deviator at the beginning of the time step s_{ijb} (b for beginning), from which we compute the equivalent stress by $(\sigma_{eq})^2 = 1.5 s_{ij} s_{ij}$; 3) the current shear modulus according to $G/G_0 = K/K_0$ [6], from which we compute the yield stress by $Y_{qs} = Y_0 G/G_0$. We then compute the effective plastic deformation rate by:

$$d_{eff}^p = A \left(\frac{\sigma_{eq} - Y_{qs}}{Y_0} \right)^\alpha \quad (4)$$

the coefficient λ by:

$$\lambda = \frac{3}{2} \frac{d_{eff}^p}{\sigma_{eq}} \quad (5)$$

and the rate of change of the components of plastic deformation rate and elastic deformation rate by:

$$\begin{aligned} d_{ij}^p &= \delta_{ij}^p = \lambda s_{ij} \\ \delta_{ij}^e &= \delta_{ij} - \delta_{ij}^p \end{aligned} \quad (6)$$

We get a system of three time-dependent ODEs for the deviatoric stress components, for each computational cell and for each time step. These equations are:

$$\dot{s}_{ij} = 2G\delta_{ij}^e \quad (ij = xx, yy, xy) \quad (7)$$

We integrate this system of ODEs across the time step with a standard ODE solver (we use the 4th order Runge-Kutta solver). At the end of such a time step we get from the integration the components of the deviatoric stress s_{ije} (e for end), from which we compute the flow stress $Y_e = \sigma_{eqe}$ by Eq. (3). We then return the flow stress Y_e to the code, which computes the components of the new deviatoric stress (for each cell) with the radial return approach originally built into the code. At this stage the code also takes into account rigid rotation of the axes, using the usual rotation correction equations.

In Fig. 4 we show results of the same problem as in Fig. 3, computed with the overstress approach, as described above.

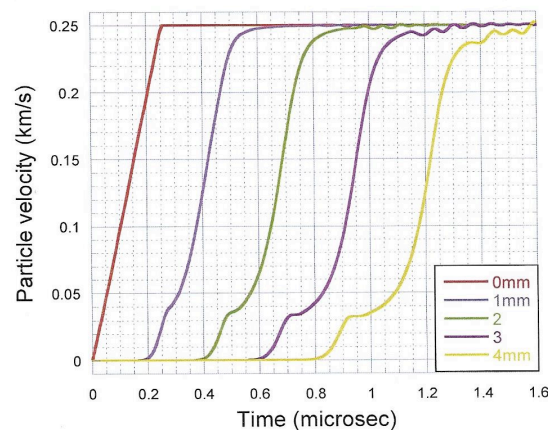


Figure 4. Particle velocity histories every 1mm into the target, from a constant acceleration of the boundary, using the overstress approach to dynamic viscoplasticity

We see from Fig. 4 that: 1) the elastic precursor wave and the transition to the plastic wave are similar to the lower part (b) of Fig. 1; 2) there is a small decay of the elastic wave, which we also discern in part (b) of Fig. 1.

We conclude that the overstress approach to dynamic viscoplasticity may perform better than the flowstress approach in predicting test results.

SPIKE FORMATION

In Fig. 1 (a) we see that spikes have formed at the starts of the elastic waves, but there are no spikes at the starts of the elastic waves of Fig. 1(b). We suspect that spike formation has to do with two parameters: 1) the rate of loading. We know that there is no spike at the start of the elastic wave for shock loading. So probably a spike may form at a not so high loading rate. In Fig. 1, tests (a) and (b) are of similar loading rates. It follows that loading rate is not the only reason for spike formation; 2) the rate of plastic flow. For the annealed material of Fig. 1(a), the initial rate of plastic flow is low, and a spike is formed. But for the cold-rolled material of Fig. 1(b) there are many dislocations, the rate of plastic flow is therefore high, and a spike is not formed. In our computations we control the rate of plastic flow by changing the parameter A . Increasing A increases the rate of plastic flow. As a result, the spike size decreases, and for high values of A it disappears altogether. The opposite happens for decreasing A . In Figs. 5 and 6 we show the influence of loading rate and the parameter A on spike formation.

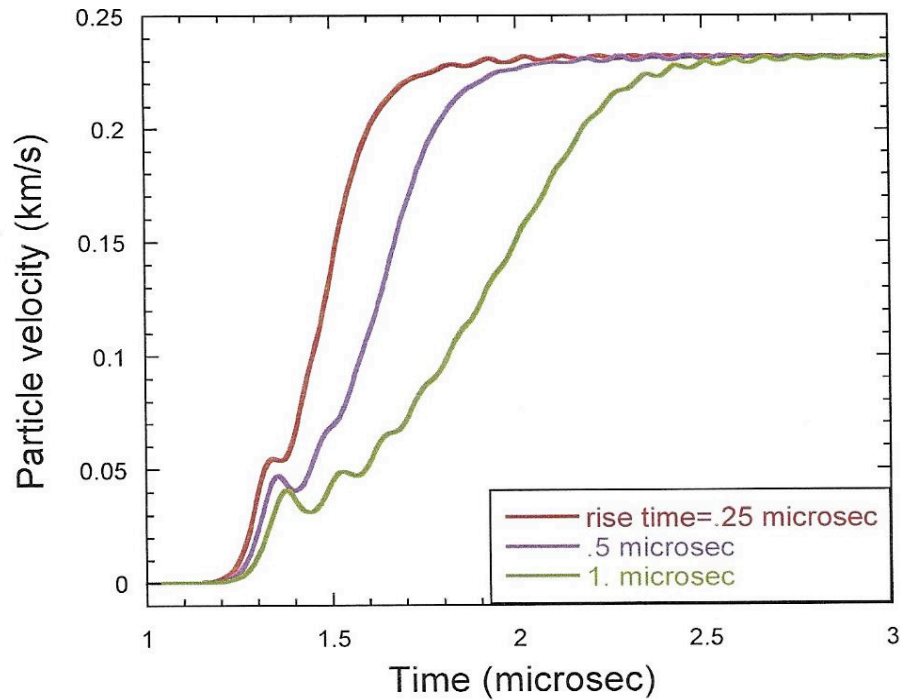


Figure 5. Influence of loading rate (or loading time) on spike formation. For a short loading time the spike disappears

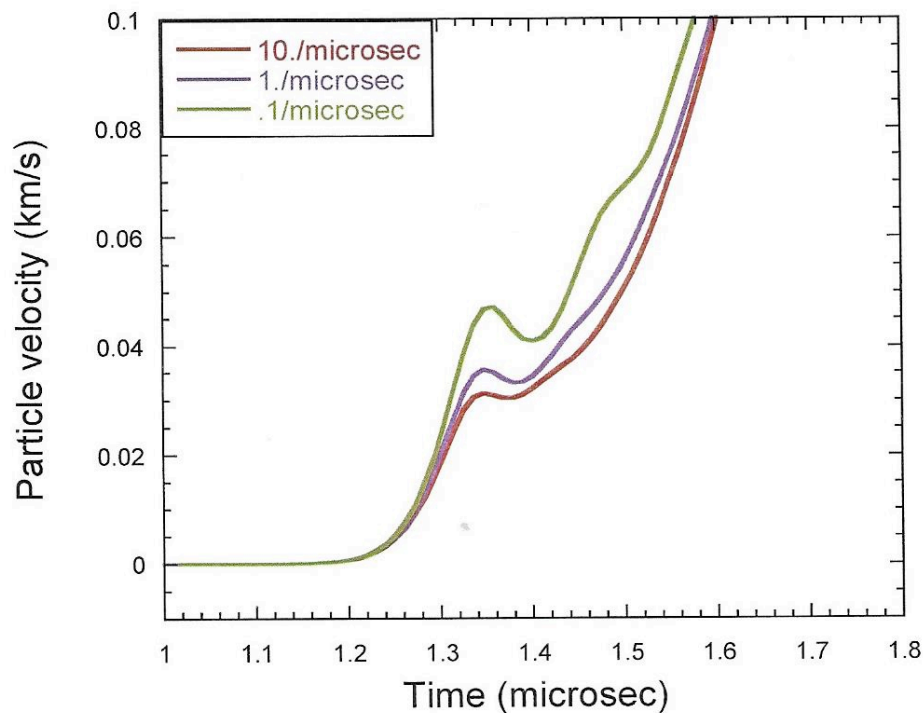


Figure 6. influence of the coefficient A. For large dislocation density the coefficient A is high, which causes a high plastic deformation rate at the same shear stress

From Fig. 5 we see that for a short loading time there is no spike. For longer loading time a spike appears and it increases with loading time (or with decreasing loading rate). From Fig. 6 we see that by increasing the parameter A (increasing the plastic deformation rate at the same stress level), we decrease the spike size until it disappears.

We conclude that by using the overstress approach to dynamic plasticity, it is possible to reproduce the response of viscoplastic materials to impact and high-rate loading, including the formation of a spike at the start of the elastic precursor.

SUMMARY

In recent years we see in the literature an increasing number of reports on gradual (non-shock) dynamic loading of metals to high pressure. The loading instrument is magnetic, and it enables to reach pressure levels of hundreds of GPa, and to perform measurements as in shock tests. In [1,2] we find results of such dynamic gradual loading tests.

High pressure dynamic tests are usually reproduced by hydrocode simulations (forward computation), and this is the common approach as long as material strength is relatively small. But for tests where material strength is the main issue, it is many times the practice to use backward analysis, and deduce material strength parameters directly from test data. Such a backward analysis may be quite complex, as in [1].

Here we perform hydrocode simulations to analyze some of the tests reported in [1]. First, we show that by using the flowstress approach to dynamic viscoplasticity, we're not able to reproduce the test results. We then convert our hydrocode to work with the overstress approach to dynamic viscoplasticity. Using the converted code, we then show that in this way we get particle velocity histories that are similar to the test results. We get elastic waves with and without an initial spike, depending on the parameter A (Eq. 2), which determines the level of plastic deformation rate as function of shear stress.

References

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