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AUTHOR(S): D. L. Tonks, R. S. Hixson, J. N. Johnson, G. T. Gray III

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Dislocation-Drag Contribution to High-Rate Plastic Deformation in Shock-Loaded Tantalum.

D. L. Tonks, R. S. Hixson, J. N. Johnson, and G. T. Gray III
Los Alamos National Laboratory
Los Alamos, NM 87545 USA

Abstract

Time-resolved plastic waves in plate-impact experiments give information on the relationship between applied shear stress and plastic strain rate at low plastic strain. This information is essentially different from that obtained at intermediate strain rates using Hopkinson bar techniques, because in the former case the material deformation state is driven briefly into the regime dominated by dislocation drag rather than thermal activation. Two VISAR records of the particle velocity at the tantalum/sapphire (window) interface are obtained for symmetric impact producing peak in situ longitudinal stresses of approximately 75 kbar and 111 kbar. The rise-times of the plastic waves are about 100ns and 50 ns, respectively, with peak strain rates of about $2 \times 10^5/s$ and $8.5 \times 10^5/s$, respectively, as determined by weak-shock analysis (Wallace, Phys. Rev. B 22, 1487 (1980), and Tonks, Los Alamos DataShoP Report LA-12068-MS (1991)). These data show a much stronger dependence of plastic strain rate on applied shear stress than previously predicted by linear viscous drag models in combination with thermal activation through a large Peierls barrier. The data also show complex evolution of the mobile dislocation density during early stages of high-rate plastic flow. This measurement and corresponding analysis aid significantly in establishing the fundamental picture of dynamic deformation of BCC metals and the evolution of the internal material state at early times following shock compression.

Introduction

Earlier work has provided a picture of weak shock wave plasticity in FCC metals.[1-5] This picture is one of dislocation dislocation interactions, rapid workhardening, and dislocation drag accompanied by rapid dislocation multiplication. No Peierls barrier (dislocation - lattice friction) is in evidence.

The shock response of BCC metals, on the other hand, has not been much studied by shock time resolved techniques. The purpose of this paper is to present some initial results for Ta, a typical BCC metal, and interpret the results in terms of dislocation behavior. This behavior is rather different from that of typical FCC metals in that a strong Peierls barrier is active and little dislocation workhardening is evident at the small strains that occur in the weak shock waves studied here

Experimental

Two Ta shots, Ta2 and Ta6, were performed with in situ shock strengths of about

75 kbar and 111kbar. The projectile velocities for Ta2 and Ta6 were 0.253 mm/us and 0.371 mm/us, respectively. The impactor thicknesses were 2.233 mm and 1.759 mm, respectively. The sample thicknesses were 5.201 mm and 4.996 mm, respectively. A VISAR apparatus was used to measure the particle velocities through a sapphire window. The Lissajous pattern for both shots were of good quality.

Theoretical Analysis

The data was smoothed somewhat. An elastic impedance correction was used to convert the Ta - sapphire interface velocity to an internal Ta particle velocity. This involved dividing the particle velocity data by 1.218. The velocity profiles resulting from both the smoothing and the impedance correction are shown in Fig. 1.

The velocity profiles of Fig. 1 were analyzed using Wallace's weak shock analysis [1] to obtain deviatoric stresses, normal stresses, plastic strains, and compressions. The Wallace analysis relies on a plausible assumption about the precursor evolution and a steady wave analysis of the main or plastic wave portion. These allow the equations of motion to be integrated to obtain, from the particle velocity profiles, normal stresses and compressions through the shock front. These quantities are then used with a thermoelastic model for material behavior to obtain the deviatoric stresses and plastic strains.

The precursor consists of the first rise and the part immediately following, both of which travel faster than the steady plastic wave portion and, thus, stretch out in front of it. In the Wallace analysis, in a time - distance plot, the precursor is assumed to stretch in a straight line between the first elastic rise and a point, called point c, where the plastic (steady) wave portion starts. The points with particle velocity 0.0372 mm/ μ s and 0.0359 mm/ μ s were chosen for point c for shots Ta2 and Ta6, respectively.

Judging by Fig. 1, the precursor stretching assumption is plausible for shot Ta2, but shot Ta6 has precursor ringing which is not included in the analysis. This ringing is probably an experimental artifact, however. For this reason, the Wallace precursor analysis probably gives good results for plastic wave portion, because the analysis has the effect of ignoring the ringing and placing a straight line through it.

The values for the shock velocity used in the analysis of shots Ta2 and Ta6 were 3.54 mm/ μ s and 3.614 mm/ μ s, respectively. They were obtained from the spread in time between the first precursor peak and the halfway point of the plastic wave portion. It was assumed that the first precursor peak traveled through the sample thickness with the longitudinal sound velocity.

The elastic constants and material density were obtained from Chhabildas. [6] The values used for λ and μ are 1.457 Mbar and 0.720 Mbar, respectively. The density value used is 16.66 gm/cm³. The values 3.79 and 1.02, obtained from Katahara [7], were used for the pressure derivatives of the bulk and shear moduli, respectively.

The calculated deviatoric stresses versus time are found in Fig. 2. In shot Ta6,

once the ringing is over with, the values should be reliable again, as noted above. Note that the final deviatoric stresses are lower than the stress of the first rise. This suggests very little work hardening through the shock path. For shot Ta6, this is exaggerated, possibly because, for this stronger shock wave and slightly thinner sample thickness, the precursor has not decayed as much as for shot Ta2. The ringing in shot Ta6 is consistent with a stronger precursor followed by a dip.

We note that the deviatoric stress used here is: $\tau = (-\frac{1}{2})(\tau_{xx} - \tau_{yy})$, where τ_{xx} and τ_{yy} are the stresses along, and normal to, the shock direction, respectively.

Fig. 3 shows the deviatoric stress versus the plastic strain. The curve for shot Ta6 (circles) has a loop near the top of the first rise due to the ringing. Comparison of the stress value for the first rise with the final stress indicates the lack of workhardening.

Both Figs. 2 and 3 show a general rise and fall of deviatoric stress through the shock front which, together with Fig. 4 for the plastic strain rate versus plastic strain, indicate a strain rate dependence of the deviatoric stress.

In Fig. 4, points with strain rates lower than $1/s$ were placed on the x-axis. The points on the x-axis at non zero strain are due to ringing and, so, are experimental artifacts.

A short error analysis was done. The sensitivity of the results was assessed, to the value of the shock velocity and to the unspecified degree of freedom in the third order elastic constants. (The two pressure derivatives given earlier are not sufficient to determine the three third order elastic constants. [2]) The results indicate that only the deviatoric stress is very sensitive to the uncertainties. The peak and final deviatoric stresses are uncertain by about 10% and 25%, respectively.

Discussion

Insight into the nature of shock wave plasticity in Ta can be obtained by comparing shock wave results with results from Hopkinson bar experiments using a plot of deviatoric stress versus plastic strain rate. Fig. 5 gives such a comparison together with results from the modeling of Hoge and Mukherjee.[8]

The shock wave results in Fig. 5 are mostly from the plastic wave portion, where most of the plastic straining occurs. The most salient feature of the shock stresses is that they lie significantly above the Hopkinson bar data and the model Peierls barrier stress for no thermally activated assistance. It is worth noting that the peak deviatoric stress of the 111 kbar shot, about 7 kbar, is significantly higher than the low temperature yield stress at low and Hopkinson bar strain rates, (not shown) which is usually about 5 kbar. These comparisons strongly suggest that the peak deviatoric stress in the shock waves is higher than the Peierls barrier; and that the mechanism of dislocation motion is dislocation drag.

Another feature is the loop formed by the shock data. In Fig. 5, the top portions of the loops for shots Ta2 and Ta6 occur early in the shock path, while the lower portions occur late in the shock path. (Note that the two late path portions overlap.

Also, the loop portions that close the loops were not plotted.) This looping indicates that the mobile dislocation density is changing. [9] For example, picking a stress occurring in a loop will yield two corresponding points with different strain rates, the one later in time being greater than the one earlier. Since the two points have the same stress, the dislocation velocities are probably the same. Therefore, since the point later in the shock path has a higher strain rate, the corresponding mobile dislocation density must be higher.

This is important in understanding the slopes of the shock curves in Fig. 5, i. e. the strain rate sensitivity. It is apparently determined both by the dislocation - velocity relation and the mobile dislocation density evolution. This combination makes the shock behavior difficult to analyze. Note, also, from Fig. 5, that the strain rate sensitivity of the Hopkinson bar data, which is known to involve thermal activation of dislocations, is roughly the same as the flatter portions of the shock waves. This similarity makes it difficult to predict, in the shock wave data, where thermal activated dislocation motion leaves off, and where dislocation drag begins. As discussed earlier, it is fairly certain that drag is operating at the peak deviatoric stress in the shock wave. It is not certain where drag becomes dominant.

The model curve with viscous drag and constant mobile dislocation density seen in Fig. 5, obviously fails to predict the shock wave strain rate sensitivity. The shock data is much less strain rate sensitive than the model prediction. This is probably due to the neglect in the model of mobile dislocation density evolution, which is important in the shock wave plasticity, as discussed above.

The lack of workhardening is evident in the shock wave data from the low values of final deviatoric stress. This is consistent with results of mechanical tests on recovered shocked Ta, in which little shock hardening is found, especially with post Hopkinson bar testing. [10] Electron microscopy indicates that edge dislocations are swept out and the screw dislocations remain straight under the influence of the high Hopkinson bar stresses necessary to overcome the large Peierls barrier. There is, thus, no good mechanism for work hardening and dislocation storage. [10]

This means that, at the end of the plastic shock wave portion, the *total* dislocation density is not much changed from its initial value. Thus, the evolution of *mobile* dislocation density evident in the shock wave results must involve mostly the freeing of dislocations already present.

In conclusion, the Ta results here suggest that the general nature of BCC shock wave behavior is dislocation drag above a strong Peierls barrier with evolution of the mobile dislocation density while the total dislocation density remains fairly constant. The strain rate sensitivity of much of the shock path is sufficiently similar to that of thermally activated Hopkinson bar data to make the separation into thermally activated behavior and drag difficult. Nevertheless, additional research to sort out these interesting effects appears worthwhile.

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Figure Captions

1. In situ particle velocity versus time. The solid and dotted lines are for waves of strength 75 (shot Ta2) and 111 kbar (shot Ta6), respectively.
2. Calculated deviatoric stress versus time. The solid and dotted lines are for waves of strength 75 and 111 kbar, respectively.
3. Calculated deviatoric stress versus plastic strain. The squares and circles are for waves of strength 75 and 111 kbar, respectively.
4. Log of the calculated plastic strain rate versus plastic strain. The squares and circles are for waves of 75 and 111 kbar, respectively.
5. Deviatoric stress versus plastic strain rate for the 75 and 111 kbar shock waves, plotted with precursor data, Hopkinson bar data, and the results of a model. The stress units here are the same as in Figs. 2 and 3.

Fig 1.

Fig 2.

Fig. 3.

Fig. 4

Fig. 5

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