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TITLE: SHOCK WAVE PLASTICITY IN NO AT 293K and 1673K

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SHOCK WAVE PLASTICITY IN MO AT 293K AND 1673K

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Abstract

The shock wave plasticity of Mo is extracted from two VISAR wave profiles; of about 110 kbar strength at 293 K and of about 120 kbar strength at 1673 K. The Wallace weak shock analysis is used to obtain the plastic strain and deviatoric stress, and the normal stress and volumetric strain, through the shock rise from the velocity profile data. The Wallace analysis uses the steady wave assumption for the plastic portion of the shock rise, a plausible evolution for the precursor portion, a thermoelastic model, and the mechanical equations of motion. Comparison of the high and low temperature results is of interest in assessing the mechanisms of plastic flow. In the results, the (von Mises equivalent) peak deviatoric stresses are 12.8 kbar and 20.3 kbar, for the hot and cold Mo, respectively, while the peak plastic strain rate of the hot Mo is about 2.6 times that of the cold Mo. These values rule out thermal activation. In addition, they are not consistent with a simple phonon viscosity linear in the temperature. Additional effects are needed to explain the results, e. g. evolution of the mobile dislocation density.

Introduction

The mechanism of plastic flow in weak shock waves, i.e. not yet overdriven, is a subject of controversy to the present day. At low strain rates, in conventional mechanical testing, thermal activation past barriers is generally accepted as the mechanism of dislocation motion. In weak shock waves, many authors (1), (2) think that dislocation drag is the mechanism. This assertion is hard to prove from data, however, due to the presence of dislocation generation, which complicates theoretical interpretation of the data. A good probe of the mechanism of dislocation motion is the temperature. Thermal activated motion should depend strongly on the temperature, for example, while dislocation drag should depend less strongly. The purpose of this paper is to present the analysis of Mo shock wave data of two very differenct temperatures, and interpret the results for the plastic flow in terms of the dislocation motion. The results are not consistent with either thermally activated motion or simple dislocation drag. Perhaps the combination of mobile dislocation evolution with simple dislocation drag could explain the results.

Data Analysis

VISAR data was obtained in digitized form from Duffy and Ahrens (3) and Furnish and Chhabildas (4). The shots analyzed were shot Mo865 at 1673 K of Duffy and Ahrens and shot CrMo4 at root temperature (293K) of Furnish and Chhabildas. The material of Duffy and Ahrens was 99.95% Ta, while the purity of Furnish and Chhabildas was not specified. These two shots had about the same shock strength: shots Mo865 and CrMo4 were of approximate strength 120 kbar and 110 kbar, respectively.

Wallace's weak shock analysis (5),(6) was used to extract plasticity information from the shock rise. This method relies on an assumption for the precursor motion and the steady wave assumption for the plastic wave portion, together with an integration of the mechanical equations of motion. The normal stress and volumetric strain are obtained thereby, from the experimental particle velocity. The shock velocity

must be known experimentally. The deviatoric stress and plastic strain are then obtained from the normal stress and volumetric strain using a thermoelastic model paramaterized from data available in the literature. See Tonks (7) for more details.

The data values used in the thermoelastic model are the following. For Mo at room temperature, the Lame constant values are 1.80 Mbar and 1.237 Mbar for λ and μ, respectively. These values are an average of those given by Wawra (8), Dickenson and Armstrong (9), Bujard et al (10), Voronov et al (11), and Bolef and de Klerk(12). The values used for the temperature derivatives of the adiabatic bulk and shear moduli, are -0.149 kbar/K and -0.179 kbar/K, respectively, obtained from Wawra. These same values were used for the 1673 K Mo, since the temperature dependence of B and μ is very nearly linear over the temperature range involved. The pressure derivative values of the isothermal bulk and shear moduli are 3.98 and 1.44, respectively, taken from Vorononv et al. The same values were used also at 1673 K. This can be justified by the shock wave results of Miller et al (13) and the thermodynamic analysis of Guillermet and Grimvall (14). The value used for the Grueneisen gamma is 1.38, taken from Voronov et al. The values used for the linear expansion coefficient and the heat capacity are 4.68 x 10^{-6} /K and .060 cal/gm K, both taken from Miller et al. The values used for D, the shock velocity, and the initial density are 5.35 mm/μs and 10.215 gm/cm^3 , from Furnish and Chhabildas.

For Mo at 1673 K, the Lame constant values used are 1.735 and 0.968 Mbar for λ and μ, respectively. The values used for the linear expansion coefficient and the heat capacity are 7.98 x 10^{-6} /K and 0.083 cal /gm K, taken from Miller et al (13). The Grueneisen gamma value used is 1.63, from White (15). The values used for D and the initial density are 5.1 mm/μs and 9.961 gm/cm^3, taken from Duffy and Ahrens (3) and Miller et al (13), respectively. The density value was obtained using Miller et al's thermal expansion formula. The value obtained is close to the one quoted by Duffy and Ahrens for 1673 K.

Note from the above that the elasticity of Mo is not much changed in going from room temperature to 1673 K, so that the thermoelastic model used at 1673 K in the calculations is reliable.

Figure 1 shows the experimental particle velocity data which has been corrected to the in situ condition. For the room temperature data, which was taken through a window, this was done by a simple impedance match. The 1673 K particle velocity data was divided by two. Only relative times are meaningful in Fig. 1. The crosses show the wave portions where the precursor is assumed to begin and end. The wave portion ahead of the first cross is assumed to be elastic.

A thorough error analysis was done to assess the effect of plausible variations in the input parameters. The quantites varied were the shock velocity, the elastic moduli, and the precursor end points. In addition, the effect of an assumption different from that used by Wallace (5), (6) about the precursor evolution was explored. It was assumed that the precursor portions traveled at speeds ranging from the longitudinal sound velocity to the shock velocity, depending on their position at an initial time. The result of these variations was that the peak deviatoric stress vaired about the values in the Figures by +- 17% for 1673 K and by +-6% for 293K. The value at the end of the shock is less reliable than the peak value, especially at 1673 K. The plastic strains and strain rates are fairly unaffected by the above uncertainty and can be considered reliable. The peak deviatoric stress is reliable enough to support the conclusions in the next section.

The analysis depends on the steady wave

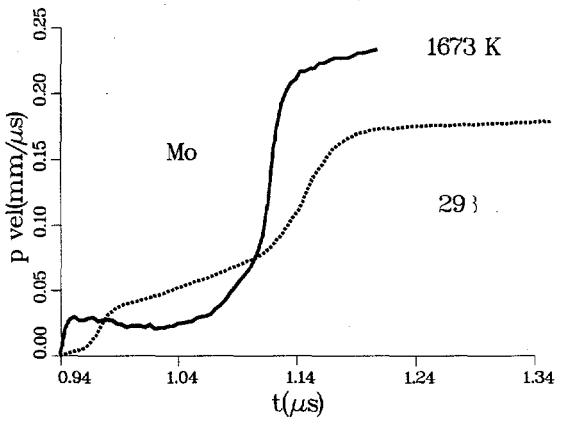

FIGURE 1 In situ particle velocity data (modified) versus time for shot CrMo4 (dotted line) at 293 K and shot Mo865 (solid line) at 1673 K.

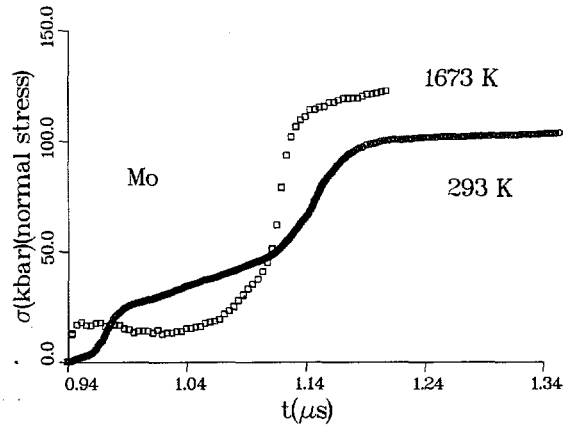

FIGURE 2. Calculated normal stress versus time for shot CrMo4(circles) at 293 K and shot Mo865 (squares) at 1673 K.

assumption for the plastic wave portion. According to Furnish and Chhabildas (4), shot CrMo4, with a sample thickness of 6.13 mm, is fairly steady. Shots at varying sample thicknesses were done. No experimental information about the steadiness of shot Mo865 is available.The sample thickness of 5.5 mm for this shot is nearly as large as for shot CrMo4, however. Also, the strain rate for shot Mo865 is larger. Thus, it could be fairly steady.

Results

The calculated in situ normal stress versus time (only relative times are meaningful) is presented in Fig. 2

The 1673 K plasticity behavior is rather different from that at room temperature, as seen in Figs. 3 and 4. The peak plastic strain rate at 1673 K is 2.6 times higher than that at room temperature, while the corresponding deviatoric stress at 1673 K is 0.63 times that at room temperature. Hence, the hot Mo shock plasticity is "softer" then that of the cold Mo.

For completeness, a plot of deviatoric stress versus plastic strain is given in Fig. 5. Note the flatness of the curve for CrMo4 at 293K and the "droop" in the curve for Mo865 at 1673K. This is evidence for lack of workharding during the shock wave loading. This lack of workhardening is evidentally a characteristic of BCC metals.(16)

The stress - strain data presented by Conrad (17)

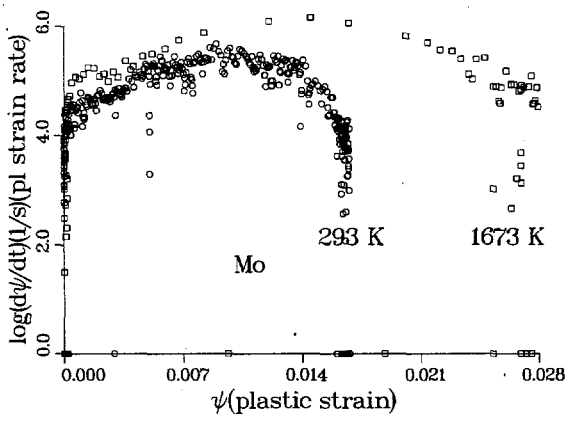

FIGURE 3. Calculated plastic strain rate versus plastic strain for shot CrMo4 (circles) at 293 K and shot Mo865 (squares) at 1673 K.

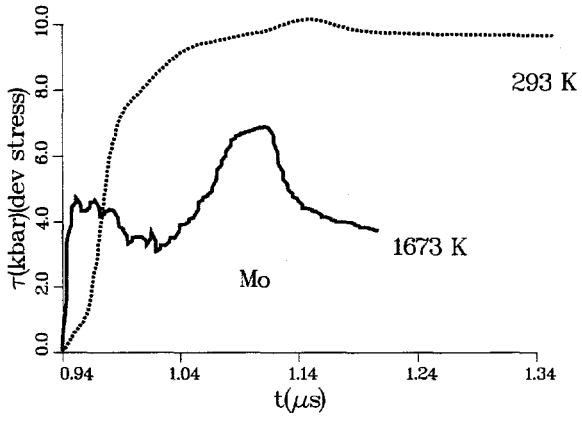

FIGURE 4. Calulated deviatoric stress versus time for shot CrMo4 (dotted line) at 293K and shot Mo865 (solid line) at 1673 K.

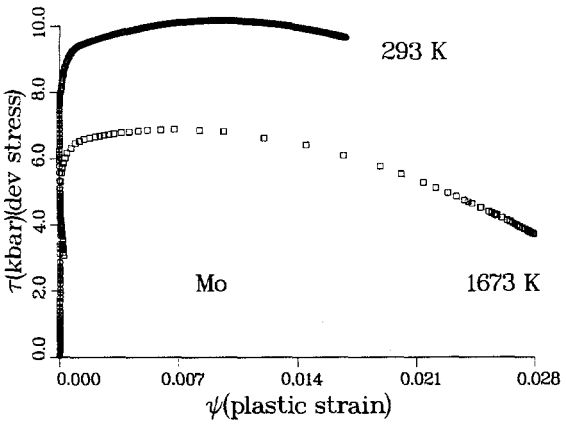

FIGURE 5. Calculated deviatoric stress versus plastic strain for shot CrMo4 (circles) at 293 K and shot Mo865 (squares) at 1673 K.

at conventional strain rates and including low temperatures can be used to asess whether the shock plasticity data is consistent with thermal activation. Conrad's data is explainable by thermally activated dislocation motion through the Peierls barrier. He extrapolates the "thermal stress" to 0 K. When one adds 0.15 kbar to his value to account for athermal stresses, one arrives at a value of .0036 for τ/g. This value is a measure of the total thermally activated barrier strength. (Here, and elsewhere, we quote the shear stress which is 0.5 times the equivalent von Mises deviatoric stress.) This value is lower than the shock HEL τ/g values and the shock peak τ/g values by quite a bit. At the HEL, our calculation produces values of 0.0058 and 0.0048 for τ/g at 293K and 1673 K, respectively. The calculation produced peak τ/g values of 0.0077 and 0.0060 for 293 K and 1673 K, respectively. Hence, at the high stress values of the shock wave, the Peierls barrier might retard dislocation motion, but does not determine it.

The possibility of simple dislocation drag behavior can be assessed by comparing ratio of τ/g at the two temperatures with the ratio of $d\varphi/dt \times T$ at the two temperatures. In the simple drag model, the plastic strain rate times the phonon viscosity should be proportional to the deviatoric stress, and the phonon viscosity should be proportional to the temperature. We will choose the shock wave points of peak plastic strain rate for this comparison. The ratio of scaled stresses turns out to be 0.78 (hot Mo/cold Mo), while the strain rate - temperatrue ratio is 14.68. Introducing a backstress, i. e. subtracting τ/g of the HEL from the τ/g values, for example, only worsens the comparison.Thus, the simple drag model doesn't explain the data either.

A likely scenario is that the dislocations are moving in dislocation drag, but accompanied by rapid mobile dislocation evolution. Such evolution would affect the strain rate in the right direction if it were greatly enhanced at the higher temperature.

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