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TITLE PLASTIC FLOW IN WEAK SHOCK WAVES IN URANIUM

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Plastic Flow in Weak Shock Waves in Uranium

Measurements of the particle velocity in weak shock waves in metals are available for a number of materials. /1/ These measurements use the laser interferometer or VISAR technique in conjunction with a plate impact experiment. These measurements are important for determining the elastic - plastic behavior of materials at high strain rates. Strain rates up to $10^7/s$ are measurable with this technique, while more conventional mechanical testing machines, such as the Hopkinson bar, achieve rates only up to about $10^4/s$.

In this paper, the VISAR measurements of Grady /2/ on uranium are analyzed using the weak shock analysis of Wallace /3/ to extract the plastic and total strains, the deviatoric and total stresses, and the plastic strain rates. A brief error analysis of the results will be given.

The Wallace weak shock analysis /3/ was used to extract stresses and strains from the particle velocity profile data. This method relies on a thermoelastic description for solids together with an integration of the mechanical equations of motion. The thermoelastic description involves an expansion of the total normal stress, σ, and of the deviatoric stress, τ, in terms of strains and entropy, to include terms of up to second order in the plastic strain, v, and the total normal compression, ϵ. ϵ is $1 - \rho_a/\rho$, where ρ_a and ρ are the initial and current densities, respectively. The plastic strain, v, can be defined in terms of ϵ and ϵ^e_{xx}, the infinitesimal elastic strain component in the shock direction, x: $\epsilon^e_{xx} = \ln(1-\epsilon) + v$. The strains are to be regarded as small and referred to the initial configuration. The normal stress, σ, is defined to be positive in compression; it equals minus the xx-component of the stress tensor. The deviatoric stress, τ, can be defined in terms of the yy- and zz- components of the stress tensor as follows: $(\sigma - 2\tau) = -\tau_{yy} = -\tau_{zz}$. The second-order equations are the following:

$$\sigma = (\lambda + 2\mu)\epsilon - 2\mu v - (1.5\lambda + 3\mu + \zeta + 2\xi)\epsilon^2 + (4\lambda + 10\mu + 4\xi)\epsilon v - (1.5\lambda + 6\mu + 1.5\xi + .25\nu)v^2 + 2\gamma \int_0^{\epsilon,v} \tau(\epsilon', v')dv' \qquad (1)$$

$$\tau = \mu(\epsilon - 1.5v) - (\lambda + 1.5\mu + \xi)\epsilon^2 + (1.5\lambda + 4.5\mu + 1.5\xi + .25\nu)\epsilon v - (9\mu/4 + 3\nu/8)v^2. \qquad (2)$$

In the above equations, λ and μ are the adiabatic *Lamé* elastic constants, μ is the adiabatic shear modulus, ζ, ξ, and ν above are equal to the third-order elastic Murnaghan constants l, m,

and n, respectively. See Wallace /3/. γ is the Grüneisen constant.

Unfortunately, measured third-order elastic constants are not available for uranium. Measured pressure derivatives of the shear and bulk moduli are available, however, and can be used with the following equations to give ν and ξ in terms of the pressure derivatives and ζ /4/: $\nu = 1.5(-3B'B - 6\zeta)$ and $\xi = (-3\mu'B - 3B - \mu + .5\nu)/3$, where B is the adiabatic bulk modulus and the primed quantities are the corresponding adiabatic pressure derivatives.

The results using the above formulas for ν and ξ are usually quite insensitive to reasonable values of ζ. This was the case for the current calculations in which a ζ-value of -5.5 Mbar was used. A theoretical reason for this in given in Ref. 1. /1/

The other part of the Wallace weak shock analysis consists of the integration of the equations of motion. As Fig. 1 shows, the velocity profiles dealt with here consist of a steady plastic portion with a precursor section that stretches out further and further with travel in front of the steady plastic portion. This precursor portion is assumed to begin with an abrupt elastic rise to a point, point b, which is seen to be roughly the same for all of the data shots. The stresses and strains for this portion of the wave were calculated using this elastic assumption.

As seen in Fig. 1, the particle velocity then grows in time until a point, point c, is reached at the base of the steady plastic portion. Point c is seen to have roughly the same particle velocity, v_c for all of the shots. The choice of point c is somewhat arbitrary. Various reasonable choices in the error analysis produced little change in the results.

The mechanical equations of motion describing the conservation of mass and momentum were integrated between points b and c of the wave profile by assuming that point b traveled with the Lagrangian sound speed, that point c traveled with the steady wave velocity, D, and that the particle velocity of the points in between varied linearly with time.

The equations of motion can be integrated along the plastic steady wave portion using the steady wave assumption. The results for ϵ and σ are the following: $\epsilon = \epsilon_c + D^{-1}(v - v_c)$, and $\sigma = \sigma_c + \rho_a D(v - v_c)$.

In the Wallace analysis, σ and ϵ are calculated first from particle velocity data as described earlier. The calculated σ and ϵ are then used with Eqs. (1) and (2) to find v and then τ.

The in situ particle velocity, or the particle velocity inside the material, must be used in the above procedure. The data, however, is measured at the free surface at the rear of the sample. In this work the free surface data was divided by two to obtain approximate in situ velocity profiles for use in the above procedure. In Ref. 5 /5/ this approximation was shown to be reasonably good

by the following means.

The characteristics wavecode CHARADE /6/ was used with the approximate in situ profile used as an initial condition to successfully predict the free surface profile for shots AV6 and AV10 for comparison with the data.

To make the wavecode calculation possible, the approximate in situ profile was analyzed in the above way to obtain plasticity information. This information was then fitted to a power-law relation giving plastic strain rate as a function of plastic strain and deviatoric stress for use in running the wavecode calculation. The power-law form used was the following: $\dot{\epsilon} = 10^d(\tau - \tau_y - h\epsilon)^g(\epsilon^c + \epsilon_a)$, where $\dot{\epsilon}$ is the plastic strain rate and τ_y is the yield stress. The fits varied somewhat according to which of the profile shots was being calculated. By way of example, the parameter values for the plastic-wave-portion of shot AV10 were the following. τ_y was $4.828x10^{-3}$ Mbar; d was 16.450; h was 0.045 Mbar, g was 3.799; and c was 0.7768. ϵ_a was .0001. With these values, τ above is in Mbar and $\dot{\epsilon}$ is in $1/s$.

The above plasticity model is appropriate for plasticity occurring during forward loading. For the reverse loading occurring during the reflection of the shock wave from the free surface, a different model must be used. For this work the reverse-loading model of Johnson et al /7/ for 6061 Al was used with a few small changes. The results of the uranium calculation were not very sensitive to the parameter values in this model which means that the good fits between calculation and free surface data did not depend much on the details of the reverse plasticity model. Hence, the wave code calculations indicate that the in situ particle velocity for uranium for the Grady /2/ data can be obtained to a fairly good approximation by dividing the free surface data by two.

Figure 1 shows the approximate in situ velocity profiles, i.e. the free surface data divided by 2, together with calculated deviatoric stresses, plastic strains, and plastic strain rates through the shock front. Note the the deviatoric stress rises abruptly with plastic strain in an elastic manner, then rises to a maximum, which coincides with the maximum in strain rate, and then falls as the point of equilibrium is reached under maximum shock pressure. The peak strain rates do not vary much with increasing shock strength, which suggests twinning.

Values of physical parameters used in the data analysis are the following. The values for λ and μ used were 0.52667 Mbar and 0.860 Mbar, respectively. The values for the isothermal pressure derivatives of the bulk and shear moduli were 5.95 and 2.99, respectively. The value 1.56 was used for the Grunelsen parameter. The value of the initial density was 18.940 g/cm^3. 31m/s was used for v_f for shot AV10. The shock velocity, D, was obtain from Grady's relation

$D = 0.249cm/\mu s + 1.370v$, where v is the peak particle velocity. /1/

In the error analysis, values for D, λ, μ, B', μ', v_c, and ζ were varied within reasonable limits in the Wallace weak shock analysis with resulting changes in the calculated τ being less than 12%. τ is the quantity most sensitive to error.

In this work, the plasticity behavior of uranium for weak shock waves has been elucidated using the Wallace weak shock analysis and wave code calculations. The results are fairly independent of error in values of the physical parameters that enter the analysis and assumptions about the reverse, i.e. unloading, plasticity that occurs at the free surface.

A complete listing of these results, together with results for seven other metals, is available in the DataShoP document /1/ available upon request from the author.

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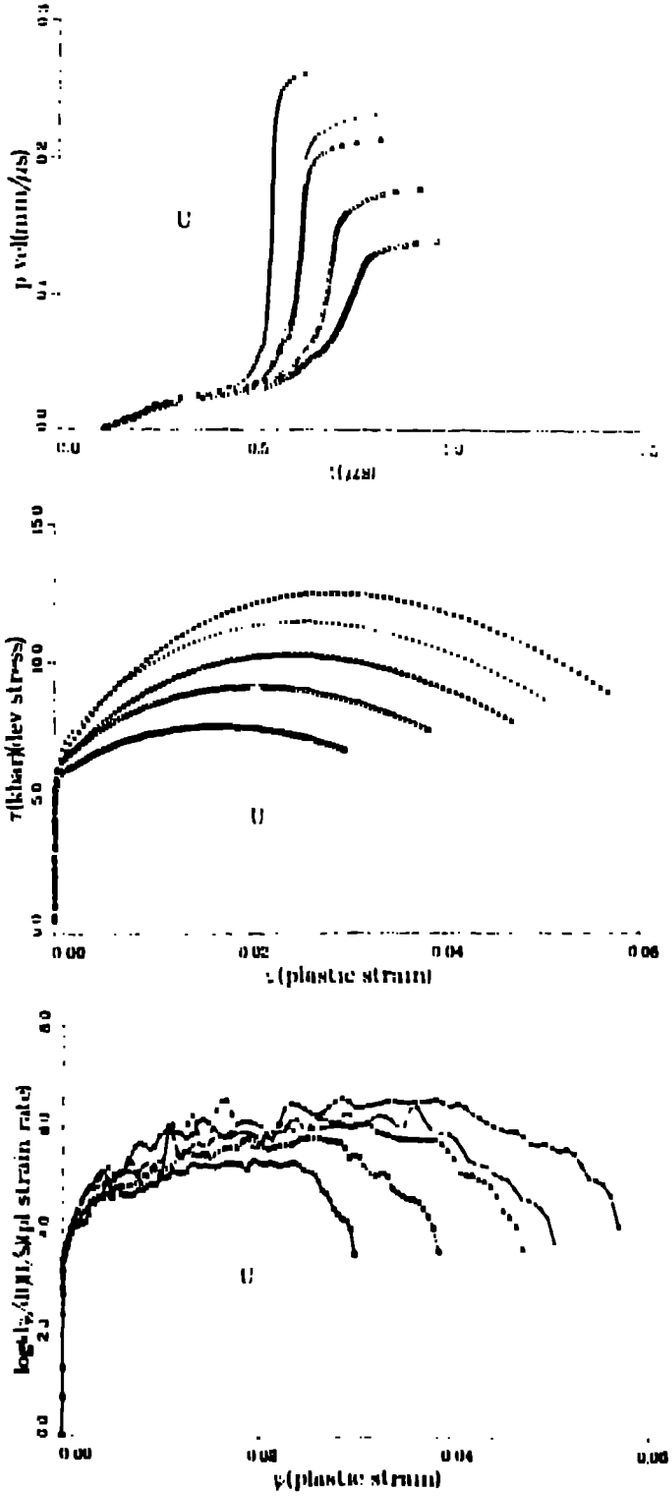

Fig. 1. Uranium shock waves. Squares, circles, triangles, pluses, and X's are for shots AV6, AV10, AV8, AV7, and AV9, respectively.
Top panel: In situ particle velocity (1/2 data) versus time.
Middle panel: Deviatoric stress versus plastic strain.
Bottom panel: Log(base 10) of plastic strain rate verus plastic strain.