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THE RATE DEPENDENCE OF THE SATURATION FLOW STRESS OF Cu AND 1100 Al

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The strain-rate dependence of the saturation flow stress of OFHC Cu and 1100 Al from 10^{-3}s^{-1} to nearly 10^{12}s^{-1} is examined. The flow stress above 10^9s^{-1} is estimated using Wallace's theory of overdriven shocks in metals. A transition to the power-law behavior $\dot{\psi} \sim \tau_s^5$ occurs at a strain rate of order 10^5s^{-1} .

1. INTRODUCTION

The flow stress of metals and alloys can be approximately determined up to strain rates of nearly 10^{12}s^{-1} with current experimental methods and theory. The constitutive behavior at rates under 10^4s^{-1} can be determined using mechanical testing machines, such as the cam plastometer and Hopkinson bar. The pressure-shear impact technique,¹ which is a variation of the Hopkinson bar, has been used to obtain large-strain data at rates from about 10^4s^{-1} to over 10^6s^{-1} . In the regime 10^9s^{-1} to 10^{12}s^{-1} , Wallace's theory² of overdriven shock waves in metals can be used to estimate the shear stress, plastic strain and plastic strain rate from data on shock velocity versus particle velocity.

In this paper we analyze OFHC Cu and 1100 Al data covering fifteen decades in strain rate. A sudden increase in rate sensitivity is evident in both at a strain rate of about 10^5s^{-1} . Above this transition point, the strain rate varies approximately as the fifth power of the saturation flow stress.

Throughout this paper we denote the equivalent plastic strain by ψ (rather than ϵ). The shear (flow) stress τ is normalized so that the incremental plastic work is given by $2\tau d\psi$.

2. THE DATA

In recent years Wallace has presented a theory for strong shock waves in metals.^{2,3} This theory incorporates both heat flow and plastic flow as dissipative mechanisms. Heat flow is necessary at the beginning of the shock wave to drive the normal stress up to values unattainable by elas-

tic deformation alone. Plastic flow is necessary later on in the shock wave to produce the enormous amounts of heat to do this.

When the strong shock is steady, as is assumed for most experimentally measured strong shock waves,² the shock velocity can be used to integrate the equations of motion to obtain the normal stress as a function of the volumetric strain. With this behavior known, the plastic flow behavior can be deduced from that of the heat flow which is known under strong shock conditions from fairly reliable extrapolations using solid state physics.^{2,3} Since the shock velocity - particle velocity behavior is known experimentally, this means that the plastic flow behavior can be inferred from the known heat flow behavior, the shock velocity - particle velocity behavior, and the known thermoelastic behavior of the material. (The latter is not known as well as one would like under Mbar shock conditions, but is known well enough to make estimates.)

The deviatoric stresses, (deviatoric) plastic strains, and plastic strain rates can, in principle, be found. The thermoelastic behavior under Mbar shock conditions is not known well enough to calculate the deviatoric stress continuously through the shock path, but an estimate of its average through the shock path can be made.^{2,3} This estimate is based on the heating effect of plastic work. The averaged deviatoric stress can then be used to calculate approximate time and space increments through the shock path from which approximations to the plastic and total strain rates can be obtained.

The integration through the shock path de-

depends on an approximation to the path of the temperature, T , versus the compression, ϵ , pictured in Fig. 1 of Ref. 3. This approximation was found by investigating bounds on this temperature path from the behavior of various ideal materials, e. g. an inviscid fluid.² The approximate path is bounded fairly closely by these considerations² and should give realistic results for the present calculations.

The first part of the path of T versus ϵ follows that of a nonplastic solid, i.e. one in which only elastic strains and heat conduction occur. This nonplastic solid path is followed until a certain point called c , at which plastic flow is assumed to become important. The T versus ϵ path from point c to the end of the shock wave is taken to be a straight line from point c to the end point on the Hugoniot, which is known from the experimental shock velocity - particle velocity relation. This straight line portion is closely bounded as described by Wallace in Ref. 3. Point c and the straight line portion are determined by requiring that the line be tangent to the nonplastic solid curve at point c .

Hence, the integration up the shock path consists of two stages. The first follows the nonplastic solid and the second follows the straight line portion where plastic flow is occurring. The first part is called the (heat) conduction front and the second is called the flow region.

The equations used here are almost identical to those used by Wallace.^{2,3} The product of $\rho\gamma$, where ρ is the density and γ is the Gruneisen parameter, is assumed to be constant. Hence, $\rho_a\gamma_a$, the value of this product for the initial condition, labeled by a , gives γ as a function of ρ . The ratio of G/B , where G is the shear modulus, and B is the bulk modulus, is assumed to be constant. This gives G as a function of B . The values 0.34 and 0.35 were used for G/B for 1100 Al and Cu, respectively. If the shock velocity, D , is given by

$$D = c + sV, \quad (1)$$

where V is the particle velocity, and c and s are constants, and if $\rho\gamma = \rho_a\gamma_a$ is assumed, then the bulk modulus is given by

$$B = \rho_a\gamma_a D^2 \epsilon (1 - \epsilon) + \rho_a c^2 (1 - \epsilon) \times [1 + (s - \gamma_a)\epsilon] (1 - s\epsilon)^{-3}, \quad (2)$$

where ϵ , the compression, is $1 - \rho_a/\rho$. The constants c and s were obtained from Ref. 4.

The heat capacity at constant volume, C_v , is given by

$$C_v = 3Nk_b + \Gamma T, \quad (3)$$

where $3Nk_b$ equals 5.9858 cal/mole K. ΓT is the electronic contribution. Γ is given by:

$$\Gamma = \Gamma(\rho_{a0}) (\rho_{a0}/\rho)^g, \quad (4)$$

where g is a constant and ρ_{a0} is the density at zero temperature and pressure. Values of 2.3×10^{-4} and 1.6×10^{-4} cal/mole K² were used for $\Gamma(\rho_{a0})$ for 1100 Al and Cu, respectively. The value $2/3$ for g was used for both 1100 Al and Cu. The values for ρ_{a0} for 1100 Al and Cu were 2.734 and 9.02 gm/cm³, respectively. The initial temperature for the shock-front calculation was taken to be 293K.

The thermal conductivity κ can be taken as a constant for the conditions here.² Values of 1.1 and 1.8 cal/s cm K were used for 1100 Al and Cu, respectively.

The shock path calculations depend on knowing the end point on the Hugoniot. This point is determined in the liquid approximation, i.e. only pressure is involved, no deviatoric stresses. For strong shock waves, where the deviatoric stress is small compared to the average stress or pressure, this should be an adequate approximation for the present purposes.

The approximate instantaneous plastic strain rate was averaged through the shock front with respect to plastic strain to obtain the values given here; this average is denoted $\langle\psi\rangle$. The plastic strain rate calculation depended upon using $\langle\tau\rangle$ in place of τ itself in equation (5) of Ref. 3, since τ itself cannot be calculated with sufficient accuracy.³

To assess the sensitivity of the results to the G/B ratio and γ , these quantities were varied about their standard values. 10% changes in G/B produced typically 5 - 10% changes in $\langle\tau\rangle/\langle G\rangle$ and a few percent changes in $\log\langle\psi\rangle$, except for Cu for the strongest shock calculated for which this quantity changed by 4%. ($\langle G\rangle$ is an average of G through the plastic flow region.) 10% changes

in γ produced typically 2 - 4% changes in $\langle \tau \rangle / \langle G \rangle$. $\log \langle \dot{\psi} \rangle$ changed by a few percent except for Cu for the strongest shock calculated for which it changed by 7%.

Data at strain rates from 10^4 s^{-1} to 10^6 s^{-1} can be obtained by the pressure-shear impact technique.¹ A thin specimen attached to an elastic flyer is sheared by impact with an elastic anvil. The shear strain rate can be varied by changing the velocity, angle of inclination and thickness of the specimen.

The specimens in six of eight experiments by Huang and Clifton⁵ on annealed OFHC Cu were prepared by the lapping of bulk material. The other two experiments involved very thin ($\sim 3 \mu\text{m}$) vapor-deposited specimens as a means of achieving strain rates over 10^6 s^{-1} . Interpretation of the data on the vapor-deposited specimens requires a thermomechanical analysis; the deformation is certainly not adiabatic, as is the deformation of the thicker specimens prepared from bulk material. Moreover, there is uncertainty regarding the constitutive behavior of specimens prepared by the two techniques. All of the data exhibit a stress plateau at strains greater than about 5%.

Twenty-seven pressure-shear experiments were performed by Li⁶ on 1100 Al. The specimens were prepared by machining discs punched from 0.625 mm thick sheets. The strain rates ranged from $2.8 \times 10^4 \text{ s}^{-1}$ to $1.8 \times 10^6 \text{ s}^{-1}$ and the hydrostatic pressure varied from 20 kbar to 30 kbar. The 1100 Al data also show saturation at strains above roughly 5%.

FIGURE 1

The Cu data: overdriven shocks (pluses), pressure-shear⁵ (triangles), Follansbee⁸ (squares), Deeg and Armstrong⁹ (circle).

There is both experimental evidence¹ and theoretical bias in support of the conjecture that the initial strain hardening rate and approach to saturation increase with the strain rate. Indeed, the pressure shear data exhibit stress saturation at a strain of about 5% for both OFHC Cu and 1100 Al. In the overdriven shock regime, where $\psi_H/2$ (Hugoniot strain) is at least of order 5%, it is reasonable to regard τ as the saturation stress for a given rate through most of the shock.

Low-rate saturation data on OFHC Cu were obtained from two sources. The saturation flow stress at 0.002 s^{-1} , 1 s^{-1} , 6000 s^{-1} and 12000 s^{-1} was determined by fitting the Hockett-Sherby hardening law to stress-strain data reported by Follansbee.⁸ A measurement of τ_s at 0.001 s^{-1} by Deeg and Armstrong⁹ is also included.

Unfortunately, low-rate saturation data on 1100 Al does not exist. As an alternative, flow stress data for $0.001 \text{ s}^{-1} < \dot{\psi} < 1000 \text{ s}^{-1}$ at $\psi = 0.08$ is included, primarily as an indicator of the rate sensitivity at these strain rates.

3. RESULTS

The low-rate, pressure - shear and overdriven - shock data on OFHC Cu and 1100 Al are collectively displayed in Figs. 1 and 2. Two observations regarding the data can be made.

(i) A rapid increase in the rate sensitivity occurs at a strain rate of order 10^5 s^{-1} for both OFHC Cu and 1100 Al; the existence of such a transition in rate sensitivity is an old issue. The errors in the

FIGURE 2

The 1100 Al data: overdriven shocks (pluses), pressure-shear⁶ (triangles), GM¹⁰ (diamonds).

data are far too small to undermine this conclusion.

(ii) It is clear from the Cu data that the saturation shear stress, when scaled by the shear modulus G , and the plastic strain rate roughly obey a power law above the transition point in rate sensitivity. Moreover, an approximate power-law behavior is not inconsistent with the 1100 Al data. Assuming a power-law relationship for each, linear least squares fits to the high - rate data yield the results

$$\dot{\psi} = 3.3 \times 10^{17} \text{s}^{-1} \left(\frac{\tau_s}{G} \right)^{5.2}, \text{ OFHC Cu}$$

(5)

$$\dot{\psi} = 6.5 \times 10^{16} \text{s}^{-1} \left(\frac{\tau_s}{G} \right)^{4.8}, \text{ 1100 Al}$$

In words, the strain rate varies approximately as the fifth power of the saturation flow stress scaled by the shear modulus.

The exponent is affected somewhat by the uncertainty in the overdriven shock results. A $\pm 10\%$ variation in τ_s implies a variation in the exponent from 5.0 to 5.4 in the case of OFHC Cu and a variation from 4.6 to 4.9 for 1100 Al. The variation in the exponent from uncertainties in $\dot{\psi}$ is insignificant.

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