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TITLE THE HEL AND RATE-DEPENDENT YIELD BEHAVIOR

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MASTER

THE HEL AND RATE-DEPENDENT YIELD BEHAVIOR

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Measurements of the Hugoniot Elastic Limit are compared with measurements of the strain-rate dependent compressive yield stress in several metals. The measurements are analyzed according to standard thermal activation theory. In several cases, only data from material from a single lot are used in the comparison. Results in Ti-6Al-4V, W, Ta, and 1018 steel are presented. It is shown that in all of the materials investigated the HEL is below the mechanical threshold stress, or yield stress at OK. Comparison of the HEL with compression measurements at low temperature and quasistatic strain rates and with compression measurements at room temperature and Hopkinson bar strain rates suggests that the strain rate associated with the HEL is on the order of 10^4 to 10^6 s^{-1}.

1. INTRODUCTION

In a weak shock wave the elastic wave outruns, i.e., travels at a higher velocity than, the plastic wave. The amplitude of the elastic wave gives the Hugoniot Elastic Limit (HEL). While it is acknowledged that the HEL represents the dynamic yield strength of the material, the quantitative connection between the HEL and the strain-rate dependent yield stress measured in quasistatic tension and compression tests is not well established. The purpose of the work described here is to present measurements of the strain-rate dependent yield stress and to show that the magnitude of the HEL in most cases is consistent with the lower strain rate measurements. Data in several materials, including tungsten, tantalum, Ti-6Al-4V, iron, and 1018 steel will be presented.

2. THEORY

Strain-rate dependent yield behavior is often described using an empirical power law of the form

$$\sigma = \sigma_1(\dot{\epsilon}/\dot{\epsilon}_1)^m \qquad (1)$$

where σ is the stress, $\dot{\epsilon}$ is the strain rate, and σ_1, $\dot{\epsilon}_1$, and m are constants. In most materials the strain-rate dependence of the yield stress arises from the thermally activated interaction of dislocations with obstacles (e.g, other dislocations, solute atoms, dispersoids, etc,). These interactions are described with a Boltzmann or Arrhenius expression of the form

$$\dot{\epsilon} = \dot{\epsilon}_0 \exp[(-\Delta G(\sigma)/kT] \qquad (2)$$

where ΔG is the activation free energy, k is the Boltzmann constant, T is the temperature, and $\dot{\epsilon}_0$ is a constant. This equation is valid for jerky glide, where the time spent by a dislocation waiting for activation energy to assist it past an obstacle provides the rate determining step. One expression that has been used to represent the stress dependence of the activation energy is written[1]

$$G = g_0 \mu b^3 \left[1 - \left(\frac{\sigma/\mu}{\hat{\sigma}/\mu}\right)^p\right]^q \qquad (3)$$

where μ is the (temperature dependent) hear modulus, $\hat{\sigma}$ is the mechanical threshold tress (flow stress at 0 K), g_o is the ıormalized total activation energy, and p 0<p≤1) and q (1≤q≤2) are constants. Although ːq. (3) with p=q=1 has been used extensively, hoosing p and q values other than unity ırovides a more physically reasonable stress lependence, particularly at high strain rates ır low temperatures. When p=q=1 and when $\sigma<\hat{\sigma}$ it s easily demonstrated that Eq. (1) is ıpproximately equal to Eq. (2), with ı=$g_o\mu b_3/kT$. However, in the general case, p≠q ınd Eq. (2) with Eq. (3) is preferred to Eq. 1). Combining Eqs. (2) and (3) and rearranging erms yields

$$\sigma/\mu=\hat{\sigma}/\mu\left[1-\left(\frac{kT}{\mu b^3 g_o}\log\frac{\dot{\epsilon}_o}{\dot{\epsilon}}\right)^{1/q}\right]^{1/p} \qquad (4)$$

In several metals, we have analyzed ıeasurements in compression at different strain ates and temperatures according to Eq. (4) to ield the unknown values of $\hat{\sigma}$ and g_{so}. We would ıow like to compare these data with measure- ıents of the HEL in identical materials (and, f possible, in identical conditions). When omparing measurements from different stress tates, however, the measurements must be ompared according to some convention (e.g., he Von Mises flow surface) to account for the tress-state dependence of the yield stress. We ill use the octahedral stress τ, defined as

$$\tau=\frac{1}{3}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)\right]^{1/2} \quad (5)$$

or uniaxial compression, $\sigma_2=\sigma_3=0$ and $\sigma_1=\sigma$, from hich it is easily shown that $\tau=0.471*\sigma$. In he elastic part of the shock wave, $\sigma_2=\sigma_3=[\nu/(1-\nu)]\sigma_{HEL}$, where ν is Poisson's ratio and σ_{HEL} is the HEL. Thus, $\tau_{HEL}=0.471[1-\nu/(1-\nu)]$. With $\nu=0.3$, for instance, $\tau_{HEL}=0.269\sigma_{HEL}$.

In standard tension and compression tests the strain rate is an input parameter and is well known. The strain rate during the elastic portion of a shock wave is, on the other hand, not well established, which complicates application of Eq. 4. Thus, in the comparisons shown below, the measured HEL is input into Eq. 4 and the resulting strain rate is calculated. A key element of the comparion will be whether the calculated strain rate is indeed a reasonable number.

3. RESULTS

A. Ti-6Al-4V. We begin with the measurements in Ti-6Al-4V because HEL and quasi-static yield stress measurements are available for a single lot of material. Morris and Gray reported the HEL as 2.8 GPa.[2] The quasistatic and Hopkinson pressure bar compression test results are shown in Figure 1.[3] The data are plotted according to Eq. (4) using uniaxial stress units; the straight line fit gives $\hat{\sigma}=954$ MPa (at 295K) and $g_{so}=0.41$. The single data point shown as a large plus sign is σ_{HEL}, converted to uniaxial stress units using $\nu=.33$. The strain rate computed from Eq. (4) is 1.6×10^5 s^{-1}.

B. Tungsten. In tungsten, again, measurements are available on a single lot of material. Asay et al. reported the HEL as 3500 MPa.[4] As in Figure 1, this measurement has been combined with our

TABLE 1. SUMMARY OF HEL AND MECHANICAL THRESHOLD SHRESS COMPARISONS

MATERIAL	σ_{HEL} GPa	ν	τ_{HEL} MPa	$\hat{\tau}$ MPa	p	q	$\dot{\epsilon}_o$ s^{-1}	$\dot{\epsilon}_{HEL}$ s^{-1}
Ti-6Al-4V	2.8[2]	0.33	619	953	1	2	10^{10}	1.6×10^5
Tungsten	3.5[4]	0.28	1008	1589	0.5	1.5	10^{10}	5×10^4
Iron	0.914[6]	0.29	255	557	1	2	10^8	1.4×10^4
1018 Steel	1.4[5]	0.29	390	814	1	2	10^9	3.6×10^5
Tantalum	1.75[7]	0.35	445	543[8]	0.5	1.5	3×10^6	8.6×10^5

·asurements of the quasistatic and Hopkinson ·essure bar compression test results in gure 2. The straight line fit gives ·1589 MPa and g_0=0.156. The strain rate during ·e elastic portion of the shock wave is timated to be 5×10^4 s^{-1}.

C. Other Materials. The results for Ta, 18 steel, and pure iron are shown in Table 1. these metals, the HEL and compression test sults are not from identical lots of terial. Nonetheless, the results are very milar to those found in Ti-6Al-4V and W. In ch case the HEL is less than the mechanical reshold stress and the estimated strain rate within the range of 10^4 s^{-1} to 10^6 s^{-1}.

DISCUSSION

The strain rates listed in the last column Table 1 are accurate to no more than plus or minus an order of magnitude because of the uncertainty in the constants $\dot{\epsilon}_o$, p, and q in Eq. (4). Nonetheless, the results do show that for the five materials studied the HEL is less than the mechanical threshold stress, when comparision is made on an equivalent stress basis. This result is outside any uncertainty in the fit of the quasistatic compression measurements to Eq. (4) or in the measurement of the HEL. The significance of this result is the implication that the HEL is determined by the same thermally activated interaction of dislocations with obstacles as occur at lower strain rates. If the HEL exceeded $\hat{\tau}$ the conclusion instead would be that the rate controlling deformation mechanisms had shifted to the viscous drag limited dislocation velocity.[9] From $\tau_{HEL} < \hat{\tau}$ it

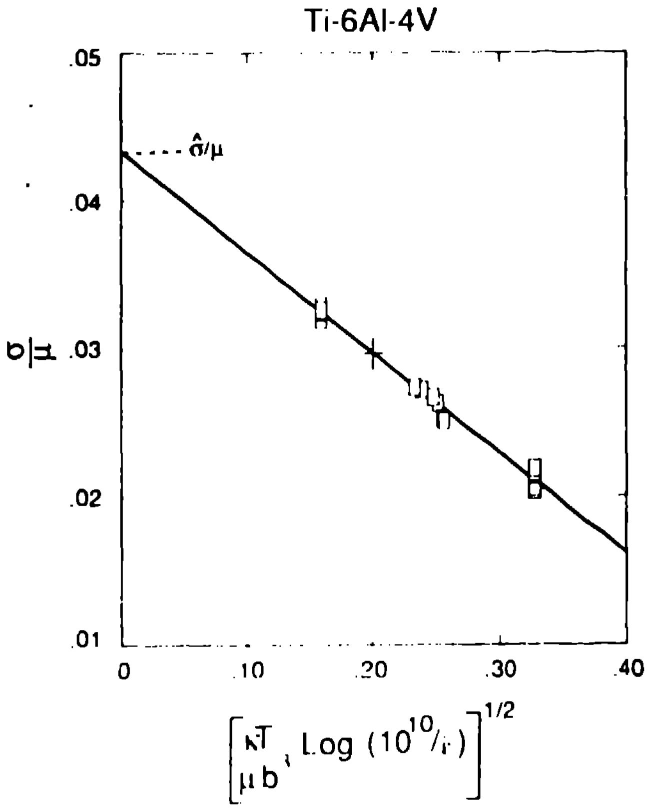

FIGURE 1
eld stress as a function of strain rate and mperature in Ti-6Al-4V. The HEL is shown th the plus symbol.

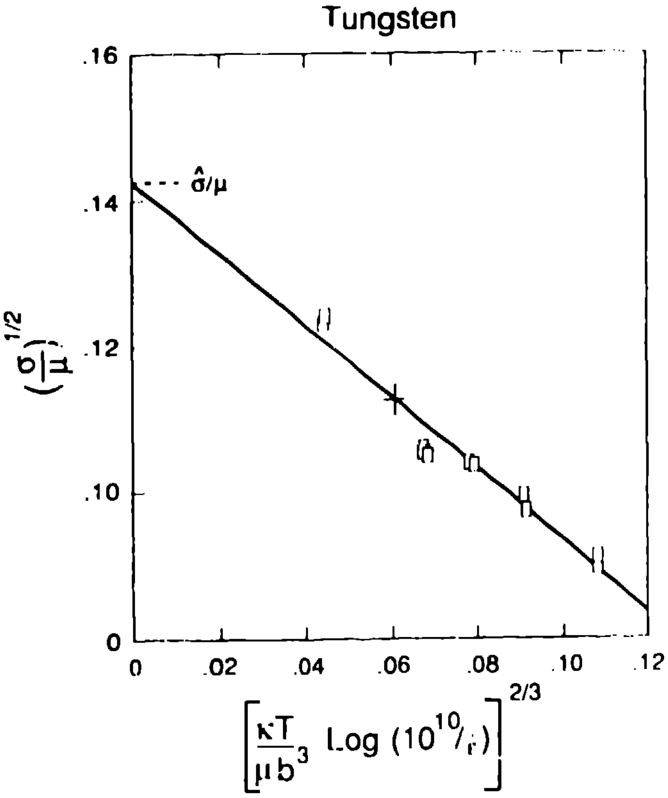

FIGURE 2
Yield stress as a function of strain rate and temperature in tungsten. The HEL is shown with the plus symbol.

llows that $\dot{\epsilon}_{HEL} < \dot{\epsilon}_0$. However, the estimated rain rates associated with the HEL are quite gh, which is consistent with expectation.

Several materials do not show a definite or nsistent HEL, which is not consistent with e analysis of rate-dependent yield behavior esented here. In annealed copper, for stance, no HEL is observed. Pure annealed pper is relatively rate insensitive. wever, the HEL should at least equal the asistatic yield strength, which when nverted to uniaxial strain units equals MPa. We do not understand why an HEL of at ast this magnitude is not observed in copper.

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