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Internal Friction and Creep-Recovery in Indium

H. Ledbetter, N. Sizova, S. Kim, H. Kobayashi*, S. Sgobba** and L. Parrini***

Materials Science and Engineering Laboratory, National Institute of Standards and Technology, Boulder, Colorado 80303, U.S.A.

** National Research Laboratory of Metrology, Tsukuba, Ibaraki, Japan*

*** CERN, Geneva, Switzerland*

**** Ecole Polytechnique Fédérale de Lausanne, Institut de Génie Atomique, 1015 Lausanne, Switzerland*

Abstract. Using low-stress pseudoshear deformation, we measured the ambient-temperature creep-recovery behavior of polycrystalline indium. The $\dot{\epsilon}$ - σ diagram shows three regions with increasing stress: stress exponents of 1.05, 7.4, and 2.0. The diagram resembles remarkably the dislocation-velocity-shear-stress diagrams reported for various materials by many authors, who interpreted the diagrams by dislocation dynamics. Applying an extended Burgers model (two Kelvin-Voigt elements) gave for the three regions the following relaxation times τ_2 and τ_3 (in seconds): (1) 11, 123; (2) 10, 132; (3) 12, 154. Thus, τ_1 is nearly stress independent, and τ_2 increases with increasing stress. Laplacean transformation of our $\epsilon(t)$ measurements to get the retardation-time distribution function $g(\ln \tau)$ indicates in all three regions a strong peak near $\tau_2 = 3$ s and a weaker, broader peak near $\tau_3 = 150$ s. These agree surprisingly well with the Burgers dashpot-spring-model results. We analyzed the recovery part of the strain $\epsilon(t)$ to obtain $Q^{-1}(f)$ curves.

1. INTRODUCTION

Creep is not only an important technological problem but also a basic solid-state physics problem where deformation often occurs by dislocation mechanisms. Measurements of creep strain $\epsilon(t)$ can be converted to $Q^{-1}(f)$, internal friction dependence on frequency.

The present study focuses on a soft metal: indium, which at ambient temperature exists at about 70% of its melting point, thus in the high-temperature region. Indium shows a body-centered-tetragonal crystal structure. In the alternative face-centered-tetragonal basis, the unit-cell dimensions are 4.947 and 4.598 Å. Thus, with an aspect ratio of 1.08, indium is not far from face-centered cubic. Indium's physical properties, such as elastic stiffness and thermal expansivity, are moderately anisotropic.

2. MATERIAL

From a commercial source, we obtained 3-kg ingots with 99.99% purity, the principal impurities being Cu, Fe, Mn. We obtained specimens by casting the indium into aluminum molds in a nitrogen atmosphere (99.95%, dry). The optical microstructure showed equiaxed grains with a wide grain-size distribution: 0.1–1 mm. By Archimedes's method, at 295 K, we found a mass density of 7.283 g/cm³, nearly exactly the x-ray-diffraction handbook value of 7.285. Using a pulse-echo measurement method, we found the following elastic constants: bulk modulus 42.2 GPa, Young modulus 12.6 GPa, shear modulus 4.35 GPa, Poisson ratio 0.450.

3. MEASUREMENTS

To measure the creep-recovery curves at various stresses, we used a method described by Kobayashi and coworkers [1]. We applied a pseudoshear force to a 1-cm-cube specimen by using calibrated masses

to a maximum of a few kilograms. We detected displacement within 10 nm by using a commercial dual-frequency Michelson laser interferometer and two cube-corner reflectors.

4. DISCUSSION

In our creep-recovery measurements, the most conspicuous feature is the enormous viscoplastic component. The total strain $\varepsilon(t)$ contains three parts: elastic, anelastic, viscoplastic. That is,

$$\varepsilon = \varepsilon_e + \varepsilon_a + \varepsilon_v . \quad (1)$$

We modeled the $\varepsilon(t)$ curve with a mechanical dashpot-and-spring model [2]:

$$2\varepsilon = \frac{\sigma_0}{M_1} + \frac{\sigma_0}{\eta_1} t + \frac{\sigma_0}{M_2} (1 - e^{-t/\tau_2}) + \frac{\sigma_0}{M_3} (1 - e^{-t/\tau_3}) . \quad (2)$$

Here, t denotes time after loading, σ_0 applied constant shear stress, M_i spring stiffnesses, η viscosity, τ_i retardation times related to the spring stiffnesses and to the in-parallel dashpot viscosities by $\eta_i = M_i \tau_i$. We added the second anelastic Kelvin-Voigt unit to the Burgers model to achieve better measurement-modeling agreement. We determined $\dot{\varepsilon}(t=\infty)$ analytically by differentiating Eq. (2) and using the coefficients determined by fitting Eq. (2) to the $\varepsilon(t)$ measurements.

The $\dot{\varepsilon}$ - σ measurements show several interesting features: At low stresses, $\dot{\varepsilon} \sim \sigma^n$ with $n = 1.05 \pm 0.08$, corresponding closely to Newtonian viscosity. At higher stresses, $\dot{\varepsilon} \sim \sigma^n$ with $n = 7.4 \pm 0.04$. We guessed, but did not verify, that the Newtonian region corresponds to Harper-Dorn creep [3]. The power-law region served as a focus of a few previous studies, both experimental and theoretical [4,5]. For this region, Weertman's model [6] predicts $n = 4.5$. His model presumes annihilation by dislocation climb of opposite-sign edge dislocations on parallel slip planes. Clearly, for our indium results, we require a model predicting $n \approx 7$. At still higher stresses, the slope decreases to about $n = 2.0$. (In Fig. 2, these three regions are labeled 1, 2, 3 in order of increasing stress.)

Some authors [7] attribute the lower slope change to the Peierls stress. We prefer to invoke the following relationship for steady-state creep (plastic-strain rate):

$$\dot{\varepsilon} = N(t) b v . \quad (3)$$

Here, N denotes mobile-dislocation density, b Burgers-vector magnitude, v dislocation velocity. Thus, an $\dot{\varepsilon}$ - σ diagram should resemble a v - σ diagram. Comparisons confirm this [8-10]. Various dislocation mechanisms associated with the S-shape v - σ curves are described elsewhere [8-10].

We can obtain the retardation-relaxation times τ from either a two-Burgers-units model, Eq. (2), or another, model-independent approach: spectral analysis. Sgobba and coworkers [11] described how the relaxation-time spectral function can be approximated:

$$g(\ln \tau) \approx \left[\frac{d}{d(\ln t)} - \frac{d^2}{d(\ln t)^2} \right] \varepsilon(t) \Big|_{\tau=t/2} . \quad (4)$$

Figure 1 shows the calculation results: a strong, sharp peak near 3 s and a weaker, broad peak near 150 s. These results agree surprisingly well with the two-Burgers-units dashpot-spring-model results. As described by Nowick and Berry [12], agreement between approximate expressions and "exact" results for the standard anelastic solid is often reasonably good.

From spectral analysis, Nowick and Berry [13] gave an approximate relationship:

$$Q^{-1} \approx -\frac{\pi}{2} \frac{d \ln J_1(\omega)}{d \ln \omega} \Big|_{\omega=1/t} \approx \frac{\pi}{2} \frac{d \ln J(t)}{d \ln t} \Big|_{t=1/\omega} \approx \frac{\pi}{2} \frac{d \ln \varepsilon(t)}{d \ln t} \Big|_{t=1/\omega} \quad (5)$$

Figure 2 shows the results obtained from Eq. (5) for the recovery part of $\varepsilon(t)$.

Figure 1: Spectrum of retardation times showing two distinct peaks.

Figure 2: Internal-friction–frequency curves obtained from Eq. (5).

5. CONCLUSIONS

1. The viscoplastic strain dominates the strain response.
2. Good agreement with a dashpot–spring model requires using two, not one, Burgers units.
3. Retardation times from spectral analysis agree reasonably well with those from a dashpot–spring model.
4. The $\dot{\epsilon}$ – σ diagram shows three regions, as found in velocity–stress diagrams.
5. Analyzing the $\epsilon(t)$ diagram gives well-defined $Q^{-1}(f)$ peaks near 0.01 Hz.

A full version of this study will appear elsewhere [14].

References

- [1] Kobayashi, H., Takahashi, H., and Hiki, Y., *Int. J. Thermophys.* **16** (1995) 577.
- [2] Nowick, A. and Berry, B., *Anelastic Relaxation in Crystalline Solids* (Academic, New York, 1972) chap. 3.
- [3] Harper, J. and Dorn, J., *Acta Metall.* **5** (1957) 654.
- [4] Weertman, J., *Trans. AIME* **218** (1960) 207.
- [5] Chevalier, G., McCormick, P., and Ruoff, A., *J. Appl. Phys.* **38** (1967) 3697.
- [6] Weertman, J., *J. Appl. Phys.* **28** (1957) 362.
- [7] Wang, J., *Scr. Metall.* **29** (1993) 733.
- [8] Gilman, J., *Micromechanics of Flow in Solids* (McGraw–Hill, New York, 1969) p. 178.
- [9] Haasen, P., *Physical Metallurgy* (Cambridge UP, Cambridge, 1978) p. 262.
- [10] Alshits, V. and Indenbom, V., in *Dislocations in Solids*, vol. 7 (North-Holland, Amsterdam, 1986) p. 46.
- [11] Sgobba, S., Parrini, L., Künzi, H.–U., and Ilshner, B., *J. Alloys Compounds* **211/212** (1994) 608.
- [12] Reference [2] pp. 49, 89.
- [13] Reference [2] p. 90.
- [14] Ledbetter, H., Kim, S., Sizova, N., Kobayashi, H., Sgobba, S., and Parrini, L., submitted.