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Internal Friction and Creep-Recovery in Indium

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Abstract. Using low-stress pseudoshear deformation, we measured the ambient-temperature creep-recovery behavior of polycrystalline indium. The $\dot{\epsilon}$-$\sigma$ 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 $\tau_2$ and $\tau_3$ (in seconds): (1) 11, 123; (2) 10, 132; (3) 12, 154. Thus, $\tau_1$ is nearly stress independent, and $\tau_2$ increases with increasing stress. Laplacean transformation of our $\varepsilon(t)$ 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 $\varepsilon(t)$ 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 $\varepsilon(t)$ 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,

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

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

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

Here, $t$ denotes time after loading, $\sigma_0$ applied constant shear stress, $M_i$ spring stiffnesses, $\eta$ viscosity, $\tau_i$ 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 $\dot{\varepsilon}$–$\sigma$ 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, $\dot{\varepsilon} \sim \sigma^p$ 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):

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

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

We can obtain the retardation–relaxation times $\tau$ 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:

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

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

Figure 2 shows the results obtained from Eq. (5) for the recovery part of $\varepsilon(t)$. 
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 $\dot{\varepsilon} - \sigma$ diagram shows three regions, as found in velocity-stress diagrams.
5. Analyzing the $\varepsilon(t)$ diagram gives well-defined $Q^{-1}(f)$ peaks near 0.01 Hz.

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

References