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ANOMALIES IN THE AMPLITUDE-DEPENDENT INTERNAL FRICTION AT LOW TEMPERATURES

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Abstract - A minimum in the temperature dependence of the internal friction observed by Pal-Val et al.[1] in Sb single crystals of various purities between 20 and 40 K, at strain amplitudes of about 10^{-6}, at 88 kHz, is shown to be a consequence of micro-creep, in which dislocations, possibly of the screw type, migrate through dilute solute-atmospheres.

In a study of the amplitude-dependent internal friction of antimony single crystals of various purities at 88 kHz, Pal-Val et al.[1] observed a minimum at 20-40 K (Fig.1), which was most pronounced in the least pure crystals. It was less developed in pre-strained ones, and barely noticeable in crystals of the highest purity. In fact, in

\[ \delta = 3 \cdot 5 \cdot 10^{-6} \exp(-y), \quad y = H/kT, \]

required by the model.

Fig. 1 - Temperature dependence of the log. dec. of an impure Sb crystal at an amplitude of 1.8 \cdot 10^{-6} in the amplitude-dependent region. Experimental results, from [1] are represented by the full line; the points comply with the relation \( \delta = 3 \cdot 5 \cdot 10^{-6} \exp(-y) \), \( y = H/kT \), required by the model.

the latter case the rate of decline of the logarithmic decrement with decreasing temperature was relatively small and almost constant over the entire range of temperatures investigated (300-6 K), approximately equal to that observed in the amplitude-independent region. The decrease of \( \delta \) between these temperature limits amounted to only about 10%. The authors [1] suggested that the unexpected increase of the decrement with decreasing temperature, below the minimum in the \( \delta/T \)-relation, was facilitated by a transition from an overdamped to an underdamped vibrational state of the dislocations: as a consequence of the low phonon-friction, dislocations which had broken away from pinning points were able to move further than at higher temperatures, and the resulting increase in the modulus-defect became manifest in an
enhanced internal friction. However, the pronounced effect of solute concentration on the extent of the anomaly detracts from an explanation in terms of an intrinsic lattice-friction. The object of this paper is to show that the observations are explicable in terms of the microcreep arising from the migration of unpinned dislocations through dilute solute-atmospheres, and that a transition in the vibrational state of dislocations need not be invoked to account for the observations.

1 - THE MODEL

We shall here consider a rather simple model applicable over a range of temperatures comprising the observed minimum in the $\delta/T$-relation, and shall assume that, following breakaway from pinning points under a static shear-stress $\sigma_s$, the effective stress acting on a dislocation after a traverse of a distance $x$ from its initial position is given by

$$\sigma_{\text{eff}} = \sigma_s - \sigma_m(x/L), \quad (1)$$

where $L$ is a structure-sensitive slip distance, and $\sigma_m$ a constant numerically close to the micro-yield stress of the crystal. Assuming a linear dependence of the energy-barrier height on stress, one has for the dislocation drift-velocity, from elementary rate theory

$$\frac{dx}{dt} = A(\sigma_s V/kT)[1 - (\sigma_m/\sigma_s)(x/L)] \exp(-H/kT) \quad (2)$$

which, with eq.(1), yields

$$x = L(\sigma_s/\sigma_m)[1 - \exp(-t/t_m)], \quad (3)$$

where $A = 2\nu rb$, $\nu$ a lattice frequency, and $r$ the number of interactomic spacing a dislocation segment advances in an activated jump. $V$ is the activation volume of the rate process, and $b$ the magnitude of the Burgers vector. The retardation time is found to be given by

$$t_m = (LH/2\sigma_m \nu rb V)/y \exp(-y), \quad y = H/kT. \quad (4)$$

With a harmonic stress $\sigma = \sigma_s \sin \omega t$ one obtains by linear superposition, with the exponential creep law $\varepsilon = pb \times$ implied by eq.(3), on using the Duhamel integral

$$\varepsilon(t) = \int_0^t \frac{\varepsilon(t-\theta)}{\sigma_s} \frac{3\sigma}{3\theta} \text{d}\theta, \quad (5)$$

the relation for the strain, and hence for the strain rate. On substituting for the latter into the equation

$$\Delta W = \int_0^{2\pi/\omega} \varepsilon(t) \frac{3\varepsilon}{3t} \text{d}t, \quad (6)$$

the logarithmic decrement $\Delta W/2W$ is, writing $W = \frac{1}{2} \sigma_s^2/G$,

$$\delta = [\pi \sigma_s blG/\sigma_m][\omega t_m/(1 + \omega^2 t_m^2)]. \quad (7)$$

Here $G$ is the shear modulus, and $\rho(\sigma_s)$ the density of migrating dislocations.

2 - COMPARISON WITH EXPERIMENT AND CONCLUSIONS

If the minimum (Fig.1) is to occur at 30 K, then $y$ in eq.(4) must be equal to 1 at that temperature, yielding $H = 2.5$ meV. On taking for the other parameters in eq.(4) $L = 3.10^{-6}$ cm, $\sigma_m = 10^{-6}$ G, $V = 10 b^3$, $Gb^3 = 2$ eV, $r = 3$, $\nu = 10^{11}$ sec$^{-1}$, $\omega = 5.10^7$.
rad/sec and \( b = 3 \AA \), one finds \( t_\omega = 2.10^{-8} \) sec for \( y = 1 \), so that \( \omega t_\omega \approx 10^{-2} \) rad at 30 K. It is readily confirmed that over the range 6-125 K, for which the shape of the curve was determined, \( \omega^2 t_\omega \ll 1 \), so that this product may be neglected in eq.(7). With \( \rho = 10^6 \) cm\(^{-2} \) the frequency independent term in eq.(7) is equal to about 3.10\(^{-1} \) and, consequently, \( \delta(30 \text{ K}) \approx 3.10^{-3} \). This value compares quite well with corresponding ones of 3.10\(^{-3} \) to about 4.10\(^{-3} \) for the antimony crystals of various purities referred to in [1].

Although the form of the temperature dependence of the logarithmic decrement is quite well encompassed by eq.(7), and an appropriate value of the modulus defect, as given by the frequency independent term in eq.(7), can be obtained on assigning reasonable values to the parameters defining it, the conclusions concerning the principal mechanism giving rise to the decrement must remain tentative. The low value of \( H \) points to a rather weak interaction of solute atoms with moving dislocations, the latter being probably of the screw type. The present analysis suggests that the minimum in the \( \delta/T \)-relation is due to solute/dislocation interactions rather than to inertial effects.

REFERENCES