MASTER

AN INCREASE IN THE INTERNAL FRICTION DUE TO ELECTRON IRRADIATION*

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Abstract

The effects of electron irradiation on the damping in high purity copper are reported for the temperature range, 78°K to 310°K. The results show an "anomalous" effect of a peak in the decrement as function of electron dose. This peaking effect can be accounted for in terms of the dislocation dragging radiation-induced point defects.

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The usual description of "dislocation pinning" in metals is as follows. In the absence of "foreign" pinners (point defects, clusters, etc.) there is an internal friction contribution due to dislocation motion in response to an external stress. Koehler¹ analysed the situation, using the following expression:

$$A \frac{\partial^2 y}{\partial t^2} + B \frac{\partial y}{\partial t} - C \frac{\partial^2 y}{\partial x^2} = b \sigma_o e^{i\omega t}. \quad (1)$$

The first term, the inertial one, will be neglected here; it is only important at high frequencies (i.e., M Hz). B is a damping coefficient ascribed to the dislocation line. Leibfried² has estimated the magnitude of B, based on phonon scattering. C is the line tension, or energy per unit length, of dislocation. In writing Eq. (1), the usual case of a stress of angular frequency ω is presented; σ_o is the amplitude of the stress. Finally $y = y(x,t)$ is the displacement of a portion of the dislocation located at a position x along the line at a time t ; b is the Burger vector. The boundary conditions are $y(0,t) = y(L,t) = 0$.

An approximate solution of this equation, which has been notably successful in accounting for many observations, was presented in detail by Granato and Lucke (G-L).³ In the kHz frequency range and below, the theory predicts that in the absence of strain-amplitude effects:

$$\delta \propto \omega \mathcal{L}_B L^4 \quad (2)$$

$$\phi \propto \mathcal{L}_L^2, \quad (3)$$

where $\mathcal{L}$ is the total length of dislocation line per unit volume, and L is the average length of dislocation between pinning points.

Irradiation experiments are particularly well suited for investigating dislocation pinning effects. The effect of irradiation, described in terms of the G-L formulation, is the introduction of additional pinning points, thereby reducing L . Koehler¹ showed that for pinning points of all varieties (impurities, point defects, dislocation nodes) arranged randomly along dislocation lines, the distribution function for free dislocation lengths is approximately

$$N(\ell)d\ell = \frac{\Lambda}{L^2} \exp\left(-\frac{\ell}{L}\right)d\ell. \quad (4)$$

This distribution function is invariant with respect to an increasing number of pinning points, so that

$$L = L_0/(1 + n), \quad (5)$$

where n is the number of additional pinning points added to an initial average free length, L_0 . Irradiation experiments are controlled means to introduce additional pinning points without changing any other parameter, in this description.

It is clear from Eqs. (2), (3), and (5) that the formulation predicts that both the decrement, δ , and the modulus defect ϕ , will decrease during irradiation as additional pinning points arrive at dislocation lines. Indeed, we are unaware of any other previous experimental observations which fail to confirm this general prediction. It is the purpose of this letter to report observations which are inconsistent with these predictions in that the decrement increases initially, reaches a maximum,

then decreases. Meanwhile, the modulus defect does decrease continually.

The principal observations are presented in Fig. 1. Each curve depicts the time dependent behavior of the decrement, normalized at its original value, as a function of the temperature at which the sample was maintained during bombardment. The samples were 99.999% pure A.S. and R. polycrystalline copper foils, previously annealed at 773°K for 30 minutes, and annealed at 773°K for 10 minutes between irradiations. The arrangement, which will be described in detail in a later report, allowed decrement and modulus readings to be made at 3 second intervals. It is similar to that reported previously by Sosin and co-workers⁴ (except that an electrostatic drive system was used here, instead of the magnetic one described in Ref. 3), but notably more sensitive.

There are two succinct features of the data in Fig. 1. The first is the time-position of the peaks. We believe that this position depends on the details of the diffusion rate at which point defects diffuse to dislocations, following their creation during irradiation. This, and related observations, are the subject of a subsequent report. Here we concentrate on the amplitude of the peaks.

The explanation of the amplitude of the peaks is complicated by a second effect which we have thus far not mentioned--the Bordoni peak. This peak is also effected by irradiation, as indicated by the initial values of decrement given in Fig. 1. In the same sequence of experiments which provide the data for Fig. 1, we have observed the reduction and eradication of the Bordoni peak which, in the temperature range reported here (above 78°K) appears as a monotonic decrease in decrement with

increasing temperature. Thus, there are two competing effects: the Bordoni peak suppression, which leads to a continual decrement decrease, and a second effect which goes through a peak as a function of irradiation dose. The rates at which these two effects manifest themselves are temperature dependent and quite different. The peaking effect, as described in a subsequent report, is fast at low temperature (i.e., at 78°K), slows toward a minimum at about 160°K, then becomes faster at higher temperature. The effect of temperature on the Bordoni peak is relatively slower at low temperature and becomes, by comparison, faster as the temperature is increased but, concurrently, becomes smaller in magnitude. The combination of these behaviors leads to the results in Fig. 1.

We are concerned in this letter only with the "peaking effect." Further information concerning its origin is presented in Fig. 2, which shows that the effect is highly structure-sensitive. The curve labelled C-22 shows the behavior of the decrement in the same sample used in the experiments of Fig. 1, but after the sample was annealed at 1053°K for ten hours. There is no peaking effect. Also shown in Fig. 2 is the behavior of a second sample, first following annealing at 1003°K for 1/2 hour (D-1)--the peak in decrement is fully evident--then following annealing at 1053°K for one hour (D-3)--no peak. We conclude that the dislocation arrangement in this general temperature region, for high purity copper with the history of the present samples, is "critical" for eliminating the peak.

The peaking effect itself, its dependence on thermal history, and the failure of other investigators to observe the peak, apparently, can be

explained in the following way. Consider again Eq. (1), neglecting the inertia term. We also consider the damping to arise from the usual line term, B_ℓ , but add the effect of the damping due to the dragging of point defects by the oscillating dislocation, nB_d , where n is the average number of point defects on a typical dislocation loop with length L between nodes. In this treatment, no lengths change; damping and modulus defect effects arise from the importance of dragged point defects.

A full analysis of this model is complex and will be presented in a later report. Here we "smear out" the individual effects of the point defects, so that the net effect is taken to be included in a single damping constant:

$$B = B_\ell + n B_d \quad (6)$$

With this approximation, it is clear that Eq. (1) is again applicable so that any behavior in damping not generally associated with the G-L theory must arise in a modified form of solution. The full solution to Eq. (1) (neglecting the inertial term) is presented graphically in Fig. 3 in a plot of δ versus μ , where μ is a "universal" parameter:

$$\mu = \left(\frac{\omega B L^2}{2C} \right)^{1/2} \quad (7)$$

The time dependence of μ is contained in B , given by Eq. (6), where it is implied that $n = n(t)$.

The shape of the decrement curve displayed in Fig. 3 can be understood by the following qualitative argument. Suppose that B_ℓ is vanishingly small, clearly, $\mu \rightarrow 0$. Place one point defect on the dislocation. Any

significant drag of this point defect by the oscillating dislocation will enhance the amount of energy being dissipated; i.e., increase the decrement. However, as the number of point defects on the line increases, the amount of dislocation motion in oscillation is sufficiently reduced that the dragging of point defects tends to become negligible; i.e., the dragging points become pinning points. The decrement is decreased toward zero. Notice that the modulus defect is continually decreased since the dislocation motion is steadily reduced.

In actuality, $B_\ell \neq 0$. Therefore, it is necessary to match the universal curve of Fig. 3 with experiment starting from the point where

$$\mu = \mu_0 \equiv \left(\frac{\omega B_\ell L^2}{2C} \right)^{1/2}.$$

Annealing in the "critical" temperature range just above 1000°K shifts the initial point, μ , from the left of (μ_p) to the right (see Fig. 3 for the definition of μ_p), so that no peak is observed. This increase in μ_0 results from an increase in L on annealing. Similarly, the failure of other investigators to observe the peak is due to either 1) working in a relatively high frequency range (kHz and above) such that a large value of ω does not allow the interstitial to be dragged, or 2) using such high rates of defect production that the first value of decrement recorded after exposure to an irradiating beam corresponds to $\mu > \mu_p$ even though $\mu_0 < \mu_p$ may have applied. The second alternative is suggested by the dotted line in Fig. 3 and may explain the apparent absence of the peak in the experiments of Keefer⁵ and colleagues, working in the same frequency range as

used in Figs. 1 and 2; the first alternative applies best to investigators working in the kHz frequency range.

Figure Captions

- Figure 1. The decrement normalized to its value at time, $t = 0$, and plotted as a function of time for the indicated temperatures. The initial decrement, $\delta_0 \times 10^3$, is given in parenthesis beside each temperature. ϕ' is the rate of production of Frenkel pairs for 1 MeV electrons. Data for the 160°K run are somewhat suspect since δ_0 appears to be anomalously large.
- Figure 2. The decrement normalized to its value at time, $t = 0$, and plotted as a function of time. The sample temperature during irradiation, the high temperature annealing temperature, and the initial decrement are: D-1 - $T_{\text{irr.}} = 290^\circ\text{K}$, $T_{\text{anneal}} = 1003^\circ\text{K}$, $\delta_0 = 2.44 \times 10^{-3}$; D-3 - $T_{\text{irr.}} = 290^\circ\text{K}$, $T_{\text{anneal}} = 1053^\circ\text{K}$, $\delta_0 = 10.7 \times 10^{-3}$; C-22 - $T_{\text{irr.}} = 320^\circ\text{K}$, $T_{\text{anneal}} = 1053^\circ\text{K}$, $\delta_0 = 2.80 \times 10^{-3}$.
- Figure 3. The theoretical value of the decrement normalized to its value at $\mu = 1$ and plotted as a function of μ . Note that the time dependence of μ is $\mu = \mu \{B[n(t)]\}$. The inset displays the normalized decrement as μ ranges from $\mu = 0$ to $\mu = 17$. E is Young's modulus; the other terms are defined in the text.

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