Dislocation-Dragging Effects in Quenched and Electron-Irradiated Copper*†

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Damping and modulus measurements were made on high-purity copper subjected to both quenching and 1.0-MeV electron irradiation. During isothermal annealing at room temperature, following quenching from 700°C, we observe a monotonic decrease in the logarithmic decrement with a concurrent increase in the modulus. However, both slow cooling and quenching of the sample followed by 1.0-MeV electron irradiation give rise to a substantial increase in the decrement; i.e., the Simpson-Sosin "peaking effect" is clearly evident.

One of the remaining problems in the field of radiation damage is the identification of the point defect or defects that cause dislocation pinning in copper near room temperature. There are three distinct and viable possibilities: (1) The normal "fast" interstitial that is observed in the stage-I (60°K) recovery region of irradiated copper with a migration energy $E_{\rm I} \approx 0.12$ eV; (2) the single vacancy with migration energy $E_v' \approx 1.0$ eV; and (3) the thermally converted stage-I interstitial with $E_{\rm II} \approx 0.64$ eV, sometimes called the "slow interstitial." For an excellent review of the status of the various defect models see the recent article by Schilling and Sonnenberg.[1]

In an attempt to determine the nature of the defects causing pinning (or dragging) at room temperature, we have performed a series of both quenching and electron-irradiation experiments on high-purity polycrystalline copper. The internal friction and modulus defect were used as monitors of the state of the dislocation pinning.

Most dislocation-pinning studies have involved the use of radiation-produced Frenkel pairs, which results in the creation of equal numbers of interstitials and vacancies in the lattice. This obviously complicates pinning experiments since it is never absolutely clear which defect one is detecting at the dislocation. This is particularly true at high temperatures where the vacancy becomes mobile. Recent work by Thompson and co-workers has indicated the presence of the slow interstitial for irradiations performed between 333 and 393°K.[2-5] Simpson and co-workers were also able to account for their observations following electron irradiation in terms of the slow interstitial.[6,7] However earlier work by Keefer and co-workers on quenched copper and gold has shown that vacancies migrate to and pin dislocations at about 300°K.[8-10] Similar observations have also been made by Roswell and Nowick on quenched gold.[11]

Simpson and Sosin[12-14] have shown that the usual interpretation of dislocation-pinning experiments in terms of the Koehler-Granato-Lücke[15-17] theory is questionable in the subkilohertz frequency range. Instead of dislocation pinning, Simpson and Sosin propose that dislocation drag of point defects is a more likely mechanism at low frequencies. The model predicts, and experiments confirm, the striking result that the logarithmic decrement can increase as a result of the addition of point defects to the dislocation line. For continuous irradiation experiments this gives rise to a peak in the decrement as a function of irradiation time. Such a phenomenon will be referred to as a dislocation "peaking effect." It seems reasonable that the drag (or pinning) of vacancies should be considerably different from the drag of interstitials. If this is so, then the presence or absence of a peaking effect could serve as a monitor of the existence of vacancies or interstitials on the dislocation.

All of our internal-friction experiments were performed on the same high-purity (99.999%) copper sample. The sample material was obtained from the American Smelting and Refining Company and machined into the form of a cantilevered beam, which could be driven electrostatically, with a flexural resonant frequency of 600 Hz. The specimen was then mounted in a special sample chamber which allowed both electron irradiation and quenching experiments to be performed. Quenches could be made from 700°C to about 15°C, with an initial quench rate of approximately 200°C/sec. For the irradiation runs, 1.0-MeV electrons were used with a flux of 6.5 $\times 10^{10}\ e^-/\mathrm{cm}^2$ sec resulting in a Frenkel-pair production rate of 2.7×10^{10} defects/cm^3 sec (close pair and correlated recovery are excluded). Young's modulus and the logarithmic decrement

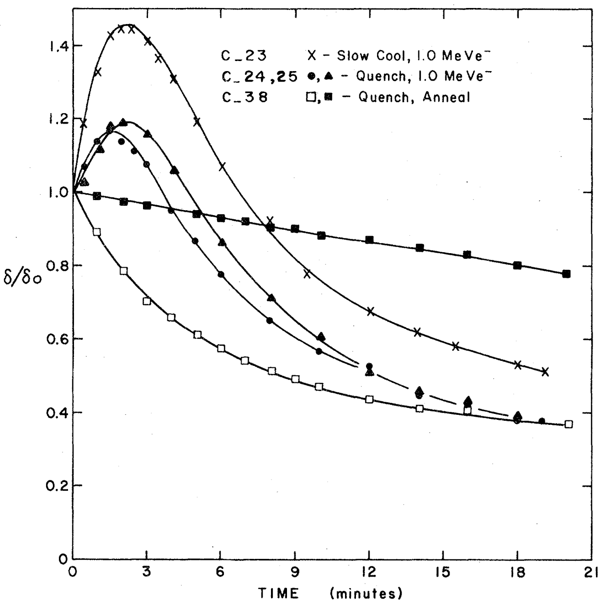

FIG. 1. The decrement normalized with respect to its initial value and plotted as a function of time. The time scale for the *open*-squares quench data is in units of 10 min.

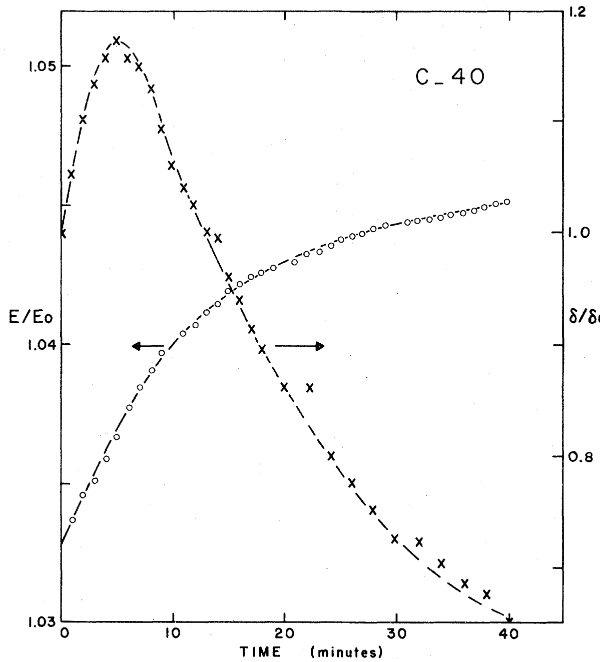

FIG. 2. The modulus normalized to its value immediately following a quench plotted as a function of irradiation time, and the decrement normalized to its value at the beginning of the irradiation and plotted as a function of time. The sample was quenched and annealed for 40 days prior to irradiation. The temperature was 26°C.

were monitored continuously. All decrement measurements were made at constant strain in the amplitude-independent region. A complete describtion of the automatic data logging system and the method of quenching will be presented elsewhere.

Experimental results for the logarithmic decrement, as affected by quenching only, quenching followed by irradiation, and slow cooling, are presented in Fig. 1. Note the large peaking effect for the slow-cool data. This is typical of results obtained for samples with this treatment. For the quench and irradiation data, the sample was quenched from 700 to 37°C and irradiation began immediately. A substantial peaking effect exists although it is somewhat subdued in comparison to the slow-cool data. Finally, a quench from 700 to 41°C with isothermal annealing at 41°C is presented. Both the early-time (solid squares) and extended-time (open squares) data give no evidence for a peaking effect, even though the possibility for such exists, since peaking occurred for the quench-irradiation run. Of course the pinning proceeds slowly for the isothermal-quench data since the lattice is being continually depleted of vacancies. These data show in a most convincing manner that the defects arriving at dislocations following quenching are entirely different from those caused by the irradiation.

A long-time (40 days) isothermal anneal was performed at room temperature following a quench from 700°C. After this extended anneal the decrement was reduced by about a factor of 4 and the modulus increased by about 3%. The sample was then subjected to the standard irradiation treatment. Results for the room-temperature irradiation are presented in Fig. 2. Even though the decrement was reduced by a factor of 4 by the post-quench annealing, the addition of radiation defects causes the peaking effect to occur. At the same time the modulus continues to increase. This indicates most convincingly that the peaking effect is not due to depinning or the modulus would decrease. It seems clear that the effect of radiation-induced defects is strikingly different from that of the quench-produced defects.

In Fig. 3 we present the results of a quench followed by an isothermal anneal at 41°C for 80 min whereupon the standard irradiation was commenced. Again, even though the isothermal annealing leads to a reduction in the decrement by

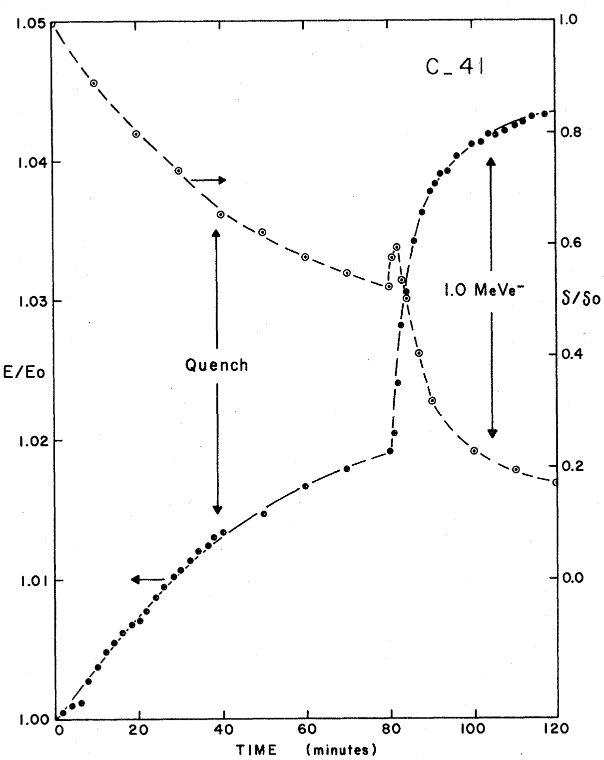

FIG. 3. The modulus and decrement normalized to their post-quench, pre-irradiation values and plotted as a function of annealing time for 80 min. Irradiation began at 80 min. The temperature was 41°C.

a factor of 2, at the onset of irradiation the peaking effect occurs. At the same time the modulus continues to increase, which rules out depinning of dislocation lines.

Additional data are presented in Table I. The subscript zero refers to the values measured at the stated temperature immediately (20–30 sec) following a quench.

The quench and irradiation data indicate most convincingly that two different defects are responsible for the dislocation-dragging (or pinning) effects in the two cases. The simplest possible interpretation of the data would be as follows. During the irradiation, the highly mobile interstitials are collected on dislocations and the resulting dragging effects give rise to the peaking effects. Following a quench, vacancies and divacancies diffuse rather slowly to the dislocation where they act more like pinning points than dragging points; i.e., the drag of a vacancy is sufficiently limited so that the peaking effect can not occur. Although the results presented here point firmly to the conclusion that interstitials arrive

TABLE I. Data for quench and irradiation runs.

Run	Condition	δ_0 (10^{-3})	$(\Delta E/E)_0$ (%)	Temp. (°C)
C-23	Slow cool	5.78	3.90	37
C-24	Quench + irr.	10.4	4.16	37
C-25	Quench + irr.	11.1	4.40	37
C-38	Quench	14.7	4.47	40
C-40	Quench + irr.	14.7	4.73	26
C-41	Quench + irr.	14.9	4.55	41

at dislocation lines during irradiation near room temperature, they do not distinguish directly between the fast and slow interstitials.

A somewhat speculative explanation of the differences in dislocation-pinning experiments at room temperature using electron and γ irradiation would be as follows. During the high defect-production-rate (2.7×10^{10} defects/sec cm^3) electron-irradiation experiments presented here and elsewhere by Simpson and co-workers,[6,7] the fast interstitial is detected on the dislocation line and since it is highly mobile gives rise to the peaking effect. In the γ-irradiation (0.25×10^7 defects/sec cm^3) experiments of Thompson and co-workers the long periods of time involved allow the fast interstitial to disappear to sinks.[2-5] Thus Thompson and co-workers measure the effects of vacancies on the dislocation.

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Effect of Structure in the Electronic Density of States on the Temperature Dependence of the Electrical Resistivity*

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I discuss the effect of sharp structure in the electronic density of states on the temperature dependence of the interband–s-d–phonon-scattering resistivity. The *a priori* density of states of Pd is used to calculate the resistivity, which is found to be in excellent agreement with experimental high-temperature results.

The temperature dependence of the electrical resistivities of the pure transition metals[1] palladium and platinum, as well as the actinide metals[2] uranium, neptunium, and plutonium, exhibits high-temperature behavior that departs drastically from the classical linear T dependence. The low-temperature behavior has been found to obey a T^2 law that has led to descriptions in terms of spin fluctuations. Similarly many intermetallic compounds, especially those exhibiting finite superconducting transition temperatures,[3,4] exhibit high-temperature resistivities that tend to bend away from linear T behavior toward the temperature axis. These compounds are usually found to obey a T^3 law indicative of s-d phonon scattering at low temperature.

The present paper involves a generalization of the model[5,6] of interband s-d (or s-f) phonon scattering for cases in which there is sharp structure in the electronic density of states $N(\epsilon)$ in the vicinity of the Fermi level E_F. It is suggested that this interband–phonon-scattering mechanism is responsible for the high-temperature resistivity behavior. Because the model does not involve the exchange-enhanced spin susceptibility as does the spin-fluctuation model of the resistivity, simple model densities of states can be used to understand the temperature dependence of both the resistivity ρ and the spin susceptibility χ.

The density of states $N(\epsilon)$ of palladium is well known from relativistic augmented-plane-wave calculations,[7,8] and I will demonstrate the resistivity calculation using the *a priori* calculation of $N(\epsilon)$. The valence electrons in the transition metals are normally divided into two groups. The first forms an s band with a spherical Fermi surface; the second, a d band with a complex Fermi surface, but with a Fermi velocity much less than that in the s band. The lattice resistivity is then divided into three parts. The first, ρ_{s-s}, describes scattering of electrons within the s band; the second, ρ_{s-d}, is due to scattering of s electrons into the d band; and the third is due to d-d scattering. Since most of the current is carried by the s electrons, only the first two processes will contribute to the resistivity due to electron-phonon scattering. The contribution ρ_{s-s} can be estimated from the resistivity of Ag, which is well behaved. We use an indirect model for the calculation of ρ_{s-d}. That is, we assume the momentum selection rule is always satisfied such that there are always phonons of sufficient size to cause interband scattering. This assumption will be invalid at very low temperatures where no phonons exist that can cause interband transitions. A Debye model for the phonon spectrum is then employed, and the resistivity is calculated following Ziman[6] except that the integral over $N(\epsilon)$ is treated generally; i.e., $N(\epsilon)$ is not assumed to be a slowly varying function of energy.