JOURNAL OF MATERIALS SCIENCE 12 (1977) 2396–2400

The effect of neutron irradiation on the internal friction of copper

H. RAHMATALLA, C. F. BURDETT
Department of Metallurgy, University of Strathclyde, Glasgow, UK

Measurements of internal friction at 1 Hz have been made on copper during continuous fast neutron irradiation at temperatures of 300, 378 and 500 K. Irradiation produced an initial increase followed by a decrease of the damping to a value below the pre-irradiation value. The decay of the damping which was interpreted in terms of the Granato–Lücke theory of strain amplitude-independent damping, was considered to be due to the decreased nobility of the dislocations through pinning by the irradiation produced point defects. Activation energies for diffusion of the defect to and along the dislocation was determined to be 0.58 and 0.38 eV respectively.

1. Introduction

Previous studies of the effect of irradiation on the dislocation damping at frequencies of the order of 1 Hz have been separated into two groups in terms of the interpretation of the results. Irradiation can produce point defects which either act as pinning points in the dislocation core thus reducing the damping by decreasing the average loop length according to the Granato–Lücke theory [1], or increase the value of the damping constant, B, according to the dislocation dragging theory introduced by Simpson and Sosin [2] so producing a peak in the damping versus irradiation time. The appearance of this peak is very much dependent on various conditions such as measuring frequency, dislocation loop length, line tension and initial values of the damping.

In a previous paper [3] the results of Simpson *et al.* [4] into the effect of electron irradiation on the dislocation damping at a frequency of 0.5 kHz were re-analysed and it was shown that the irradiation produced point defects can pin the dislocation lines and shorten the loop length according to the Granato–Lücke theory [1]. A model was developed relating the damping to the number of point defects per dislocation segment introduced during electron irradiation. Good agreement of the results with theory was obtained. In the present work this model has been extended to the effect of continuous neutron irradiation on the internal friction of copper at low frequencies.

2. Experimental

The experiments were performed on high-purity polycrystalline copper (99.999%) obtained from Johnson–Matthey in the form of rods, 0.5 cm diameter and 15 cm long, from which wires, 0.075 cm were drawn. After drawing they were cut into lengths of approximately 5.5 cm, sealed into silica tubes and annealed at 600° C for 1 h. A sample of annealed wire was then mounted into an inverted torsion pendulum; the effective length of the specimen was 4.5 cm and the strain amplitude was 2×10^{-5}.

The internal friction was obtained by measuring the logarithmic decrement of free vibration. Irradiation was performed *in situ* using Californium 252 as a fast neutron irradiation source and a flux density of 0.27×10^{7} neutrons per cm^2 per sec was obtained at the specimen. Torsional deformation and annealing were also carried out *in situ*. Further details of the experimental techniques have been published elsewhere [5].

3. Experimental results

A sample deformed 52% in torsion and annealed for 30 min at 773 K *in situ* was irradiated at 300 K. The damping was measured during the irradiation

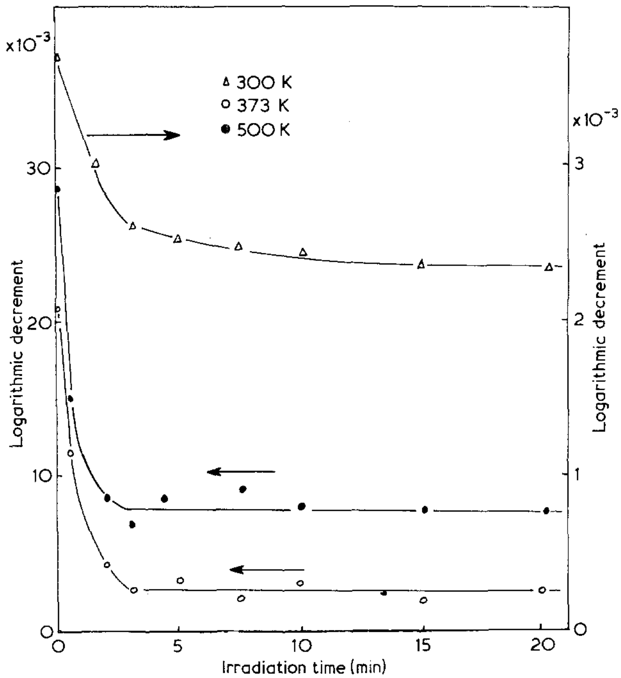

Figure 1 The effect of irradiation on the damping of copper deformed 52% in torsion; △ 300 K, ○ 373 K, ● 500 K.

procedure and the results are shown in Fig. 1. A second and third specimen were given similar pre-irradiation treatment. The damping was then measured during neutron irradiation at temperatures 373 and 500 K respectively. The results are shown in Fig. 1.

The damping initially increased to reach a maximum after an irradiation of approximately 1 min at all temperatures. Further irradiation caused the damping to progressively decrease, eventually reaching values below the pre-irradiation levels. It has been shown [5] that the internal friction can be separated into two components; an internal friction peak superimposed on a general decay of the damping with increasing time of irradiation. The results in Fig. 1 simply show the decay of the damping with irradiation. The peak effect has been separated and will be reported on later.

4. Discussion

In an earlier paper the authors showed that the decrease in dislocation damping during electron irradiation could be explained on the Granato–Lücke model for strain amplitude independent damping if due consideration was given to the continuing production of defects and to diffusion of these defects along the dislocations.

The decrease of the damping during irradiation is due to the pinning of the dislocations by the irradiation-induced point defects, thus shortening the average loop length L. The number of point defects per dislocation segment added to the dislocation during the period of irradiation can be obtained from the relationship.

$$n = \left[\frac{\delta - \delta_e}{\delta_0 - \delta_e}\right]^{-1/4} - 1 \qquad (1)$$

where δ_0 and δ_e are the initial and the saturation value of the damping and δ is the damping after time t.

Assuming that neutron irradiation produces point defects which subsequently diffuse to the dislocations, n can be related to the time through the Cottrell–Bilby relation [6]. Specifically, a plot of log n versus log t should be a straight line of slope equal to the Cottrell–Bilby exponent. Fig. 2 shows such a plot of the results obtained from Fig. 1. The plots are linear but the slopes depend on temperature, increasing with decreasing temperature. A summary of the slopes is given in Table I(a).

TABLE I

(a) T (K)	Slope	(b) T (K)	Slope
300	1.4	0.01	1.497
373	1.09	0.1	1.397
500	0.9	1.0	1.04

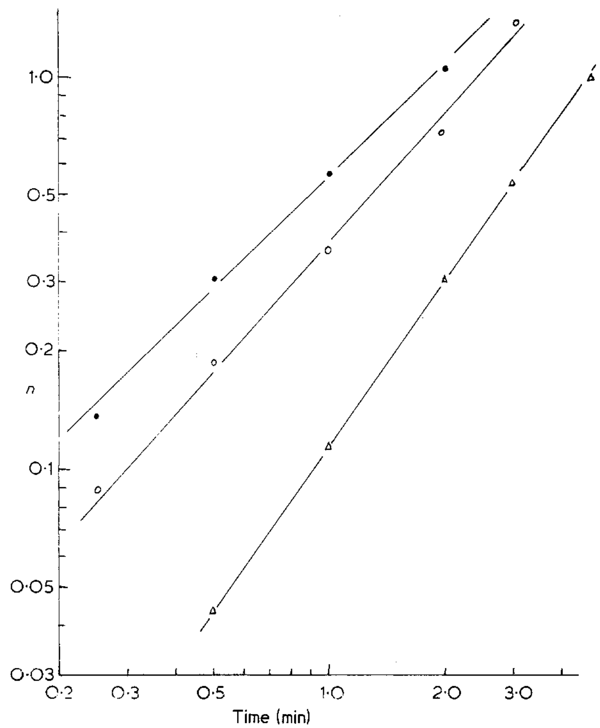

Figure 2 The logarithm of the number of point defects produced as a function of the logarithm of the irradiation time for the indicated temperatures; △ irradiation temperature 300 K, ○ irradiation temperature 373 K, ● irradiation temperature 500 K.

The behaviour of the damping during neutron irradiation is similar to that observed during electron irradiation [4], and two suggestions were put forward in an earlier paper [3] to explain the lack of complete agreement with the Cotrell–Bilby equation. Briefly these are: (1) in the derivation of the Cottrell–Bilby equation it is assumed that there is no generation of defects in the lattice; (2) no allowance has been made for the possible diffusion of defects along the dislocations which will obviously reduce the pinning effect.

In an earlier paper a model was developed to explain the change in damping during electron irradiation. Electron irradiation produces point defects in the lattice which can then diffuse to the dislocations. Because of the temperatures involved, diffusion of the defects along the dislocations to nodal points is possible. The change in damping produced during continuous irradiation is therefore caused by the net change in point defect density on the dislocations.

A similar process can be envisaged for the case of neutron irradiation and will be applied to the results. The analysis for the case of neutron irradiation is slightly different because for neutron irradiation, the production rate of point refects in the lattice is constant [9], i.e. $\mathrm{d}c/\mathrm{d}t = \Phi$ [2], where Φ is a constant dependent on the flux. The point defects diffuse to the dislocations with a diffusion coefficient D. As the defects arrive at the dislocations it is possible for them to diffuse along the dislocations with a diffusion coefficient D'. The rate of increase in the number of point defects per dislocation segment is given by

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \frac{\mathrm{d}N}{\mathrm{d}t} - Kn \tag{3}$$

where N is the number of point defects arriving at the dislocation segment of length L. K is the rate at which point defects leave the dislocation segment at nodal points and is given by

$$K = \frac{\pi^2 D'}{L^2} \tag{4}$$

where

$$D' = D'_0 \exp(-Q'/RT), \tag{5}$$

where Q' is the activation energy for diffusion of point defects along dislocation lines.

The arrival of the point defects at the dislocation is governed by the Cottrell–Bilby equation,

$$N = AC(t)t^{1/2}, \tag{6}$$

where $C(t)$ is the concentration of point defects in the lattice and is a function of time during continuous irradiation.

$$A = A_0(D/T)^{1/2}, \qquad (7)$$

and

$$D = D_0 \exp(-Q/RT), \qquad (8)$$

where Q is the activation energy for diffusion of the point defects to the dislocation and A_0 and D_0 are constants. Substituting Equation 2 into Equation 6

$$N = A\Phi t^{3/2}.$$

From Equation 3

$$\frac{dn}{dt} = \tfrac{3}{2}A\Phi t^{1/2} - Kn. \qquad (9)$$

The solution to Equation 9 with the condition that at $t = 0, n = 0$, is

$$n = A\Phi t^{3/2}\left[1 - \frac{2Kt}{5} + \frac{(2Kt)^2}{5.7} + \frac{(2Kt)^3}{5.7.9} + \ldots\right] \qquad (10)$$

For small values of Kt, the terms inside the brackets can be expressed as $\exp(-\alpha Kt)$, where α is a numerical constant of value approximately 0.36. Thus Equation 10 becomes

$$n = A\Phi t^{3/2} \exp(-\alpha Kt). \qquad (11)$$

At low temperatures and not very long times of irradiation ($Kt < 1$), a plot of $\ln(n)$ versus $\ln(t)$ should be a straight line of slope equal to 1.5. At higher temperatures, K increases and the slope of $\ln(n)$ versus $\ln(t)$ should decrease.

Fig. 3 shows the theoretical plot of Equation 10 for different values of K. The values of the slopes obtained from Fig. 3 are given in Table I together with the slopes obtained from the experimental results in Fig. 2. Comparison indicates a hundred fold change in K over the temperature range 300 to 500 K.

For small values of Kt, Equation 11 predicts that a plot of $\ln(n/t^{3/2})$ versus t should be a straight line; the results are plotted in Fig. 4. As predicted, for small values of Kt, either low temperatures for long times or at higher temperatures for shorter times, Equation 11 holds. The values of the slopes S and intercepts I increase with increasing temperature. From Equation 11 and Equations 7 and 8,

$$\ln(I \times T^{1/2}) = \text{constant} - \frac{Q}{2RT}, \qquad (12)$$

and from Equation 11 and Equations 4 and 5

$$\ln(S) = \text{constant} - \frac{Q'}{RT}. \qquad (13)$$

Inserting the values of the slopes and intercepts obtained from Fig. 4 into Equations 12 and 13 respectively yields the activation energy of 0.58 eV

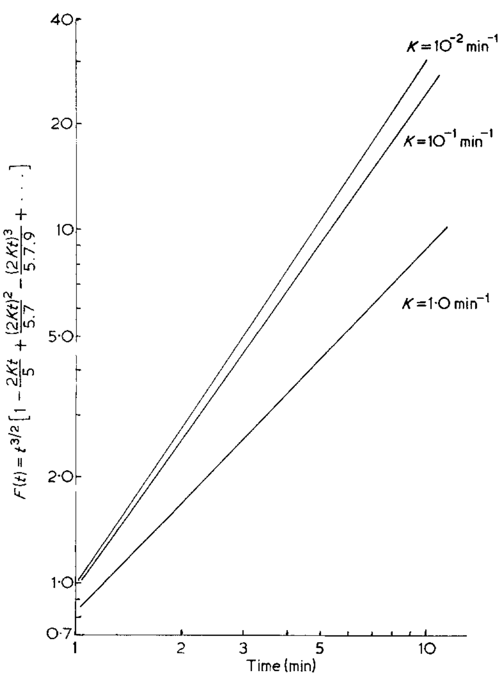

Figure 3 The theoretical plot of $F(t)$ from Equation 10 for the indicated values of K.

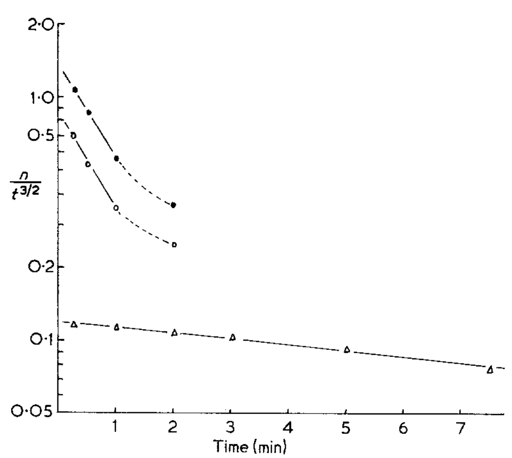

Figure 4 $n/t^{3/2}$ versus irradiation time for the indicated temperatures. △ 300 K, ○ 373 K, ● 500 K.

for the migration of the defects to the dislocations and 0.37 eV for diffusion of the defects along the dislocations.

Thomson *et al.* [7] have obtained a value of 0.64 eV for the migration energy of point defects to dislocations over the temperature range 333 to 393 K in γ-irradiated copper. Meisel and Thompson [8] obtained a value of 0.61 eV for the migration of defects over a similar temperature range after γ-irradiation. Interstitials were considered to be the pinning defect. The value of the migration energy in this work is in good agreement with earlier results.

The value of the activation energy for the diffusion of the defects along the dislocations has been calculated to be 0.38 eV and is comparable to the pipe diffusion data obtained after γ-irradiation [7] and during electron irradiation [2].

5. Conclusions

The damping decrease observed during continuous neutron irradiation has been successfully analysed in terms of the Granato–Lücke theory, when due consideration is given to a continuing defect production and to pipe diffusion.

References

1. A. GRANATO and K. LÜCKE, *J. Appl. Phys.* **27** (1956) 583.
2. H. M. SIMPSON, A. SOSIN, *Phys. Rev.* **B5** (1972) 1382.
3. C. F. BURDETT and H. RAHMATALLA, *J. Mater. Sci.* **12** (1977) 843.
4. H. M. SIMPSON, A. SOSIN and D. F. JOHNSON, *Phys. Rev.* **B5** (1972) 1393.
5. H. RAHMATALLA, Ph.D. University of Strathclyde, (1976).
6. A. H. COTTRELL and B. A. BILBY, *Proc. Phys. Soc.* **A62** (1949) 49.
7. D. O. THOMPSON, O. BUCK, H. B. HUNTINGTON and R. S. BARNES, *J. Appl. Phys.* **38** (1967) 3051, 3057.
8. L. MEISEL and D. O. THOMPSON, *ibid* **39** (1968) 3447.
9. A. C. DAMASK and G. J. DIENES, "Point Defects in Metals", (Gordon and Breach, New York, 1963).

Received 21 February and accepted 13 May 1977.