

On the background damping in the vicinity of the grain-boundary damping peak in zinc

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The background damping in the vicinity of the grain-boundary damping decreases with increasing grain size. An analysis of the strain amplitude dependence of this damping shows that as the grain size increases the distance between solute pinning atoms on dislocation decreases. This can be explained in terms of a movement of solute away from grain boundaries and to dislocations. Thus as the grain size increases the total number of solute atoms at grain boundaries decreases and is rejected both into the lattice and to dislocations. A mathematical model is used to explain this result. As a consequence an activation energy of 0.05 eV is obtained for the binding energy of the solute to the dislocation.

1. Introduction

In 1947 Ke [1] measured the temperature dependence of the internal friction of aluminium, copper and iron and found a peak at a temperature of about half the absolute melting temperature. He called this the grain-boundary peak because it was observed only in polycrystalline materials.

In all of the materials studied so far the grain-boundary peak sits on a background damping which increases with temperature and for which no satisfactory explanation has yet been given. The background damping is probably related to the grain-boundary damping in some way since it increases with decreasing grain size. However, grain interior processes contribute substantially to the background relaxation, for it is clearly observed in single crystals as well as polycrystals.

The first explanation for this background damping was proposed by Zener [2] who considered that the damping arose from plastic deformation at grain corners caused by stress concentrations at these points. In the model proposed by Friedel *et al.* [3] it was suggested that the stress induced climb and glide of dislocation arrays caused the

damping. Thus according to this model the activation energy for the damping process should be the formation and migration energy of the vacancies since the process requires the absorption or emission of vacancies at dislocation jogs.

It appears that there are, at present, no sufficiently detailed measurements on the background damping to allow a quantitative comparison of theory and experiment. Since grain interior processes as well as grain-boundary processes contribute to the damping, it was decided to carry out experiments into the strain amplitude dependence of the background damping specifically to determine quantitatively the effect of grain size. Zinc was chosen because the grain-boundary peak has been fully investigated and because the peak temperature was only 130°C [4].

2. Experimental

The apparatus consisted of an inverted torsional pendulum evacuated to a pressure of less than 1×10^{-5} Torr, with an optical lever to increase the accuracy of the results. The strain amplitude could be varied over the range 1 to 30×10^{-5} and

the damping capacity was obtained as the logarithmic decrement of the decay of natural vibrations. The frequency of measurement was 1.5 Hz.

99.975% pure zinc containing 0.015% lead and 0.005% cadmium was drawn into wire of diameter 0.7 mm. A sample, 25 cm long was placed in the apparatus together with a dummy sample for grain size measurement. The wires were annealed at 373 K for $\frac{1}{2}$ h, slowly cooled to room temperature and the damping was measured as a function of strain amplitude. The temperature was then reduced to 226 K using a solid carbon dioxide/alcohol mixture and again the damping was measured as a function of strain amplitude. The temperature was increased to 334 K and the experiment was repeated. A piece of wire was removed from the dummy sample and the grain size was measured.

The zinc wires were then heated at 100°C for 12h, cooled slowly to room temperature and the damping was measured as a function of strain amplitude at 226, 294 and 334 K. Again a piece of the dummy sample was removed and the grain size was measured.

This procedure of heating to 100°C followed by the measurement of the internal friction at 226, 294 and 334 K was repeated six times. A sample was removed for grain size determination after each stage.

3. Results

Logarithmic decrement versus strain amplitude at temperatures 226, 294 and 334 K are shown in Figs. 1 to 6 for increasing grain size. The grain sizes of the samples are given in Table I. Most results exhibit a plateau region at an approximate strain amplitude of 2.5×10^{-5} after an initial steep increase in the damping. At higher strain amplitudes the damping is dependent on the strain amplitude.

TABLE I

| Experiment no. | Slopes from Granato-Lücke plots ($\times 10^4$) | | | Grain size (mm)($\times 10^3$) |
|----------------|---|-------|-------|----------------------------------|
| | -37°C | +21°C | +61°C | |
| 1 | 4.0 | 3.08 | 2.2 | 19.0 |
| 2 | 5.0 | 3.1 | 2.58 | 26.1 |
| 3 | 5.41 | 3.1 | 2.20 | 30.3 |
| 4 | 7.1 | 3.6 | 2.10 | 33.4 |
| 5 | 6.5 | 3.3 | 2.38 | 40.4 |
| 6 | 7.3 | 3.3 | 2.80 | 44.2 |

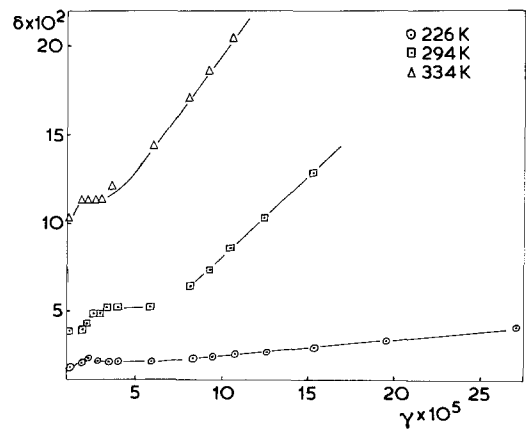


Figure 1 Logarithmic decrement (δ) versus strain amplitude (γ), grain size $d = 19.0 \mu\text{m}$.

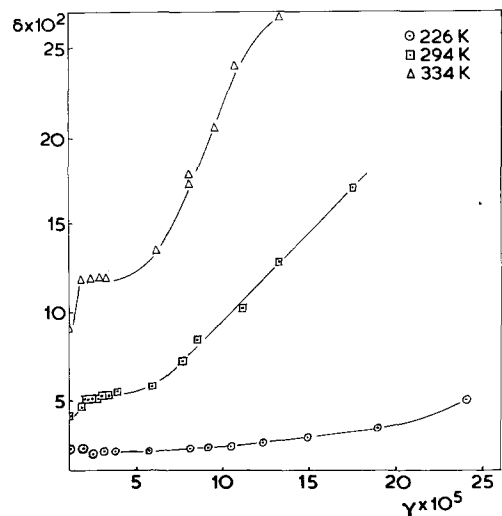


Figure 2 Logarithmic decrement (δ) versus strain amplitude (γ), grain size $d = 26.1 \mu\text{m}$.

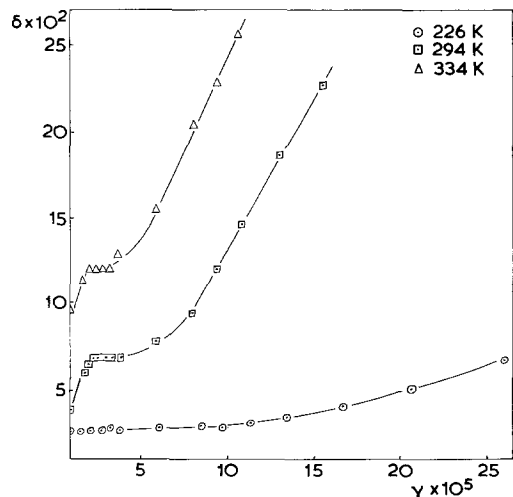


Figure 3 Logarithmic decrement (δ) versus strain amplitude (γ), grain size $30.3 \mu\text{m}$.

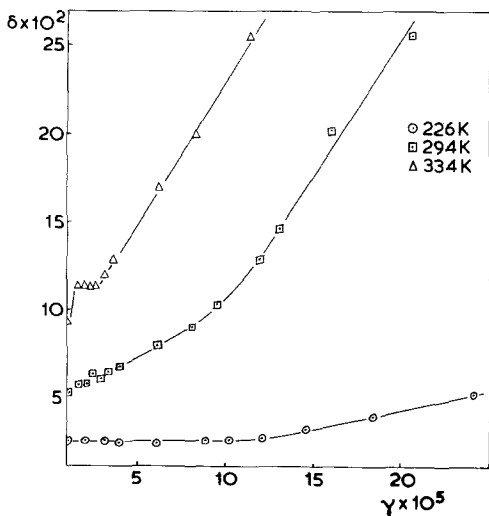


Figure 4 Logarithmic decrement (δ) versus strain amplitude (γ), grain size 33.4 μm .

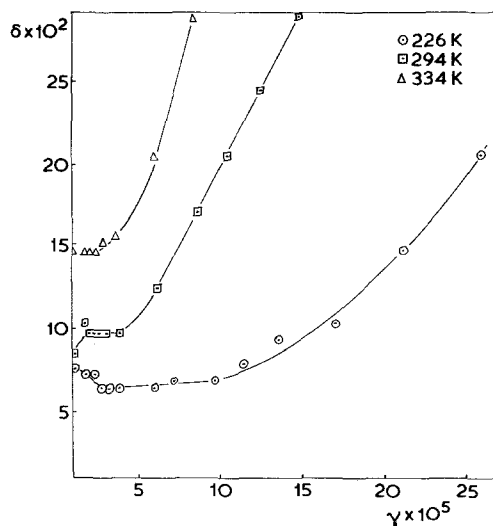


Figure 6 Logarithmic decrement (δ) versus strain amplitude (γ), grain size 44.2 μm .

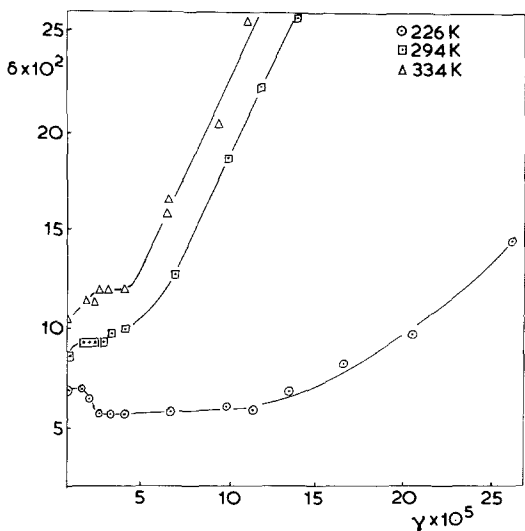


Figure 5 Logarithmic decrement (δ) versus strain amplitude (γ), grain size 40.4 μm .

As the temperature increases, the magnitude of the strain amplitude independent damping increases (low temperature side of the grain-boundary peak). The rate of increase of the strain amplitude dependent damping also increases with temperature.

Apart from the plateau region, the damping consists of two components

$$\Delta_T = \Delta_I + \Delta_H$$

where Δ_I is the strain amplitude independent damping and Δ_H is the strain amplitude dependent damping. From the Granato-Lücke model

$$\Delta_H = \frac{A}{\epsilon} \exp \left[-\frac{B}{\epsilon L_c} \right]$$

where L_c is the length of dislocation between solute pinning points, ϵ is the strain amplitude and A and B are constants.

A plot of $\log [\Delta_H \cdot \epsilon]$ versus ϵ^{-1} should be linear with a slope proportional to L_c^{-1} . Figs. 7, 8 and 9 show the Granato-Lücke plots for the six different grain sizes at temperatures 226, 294

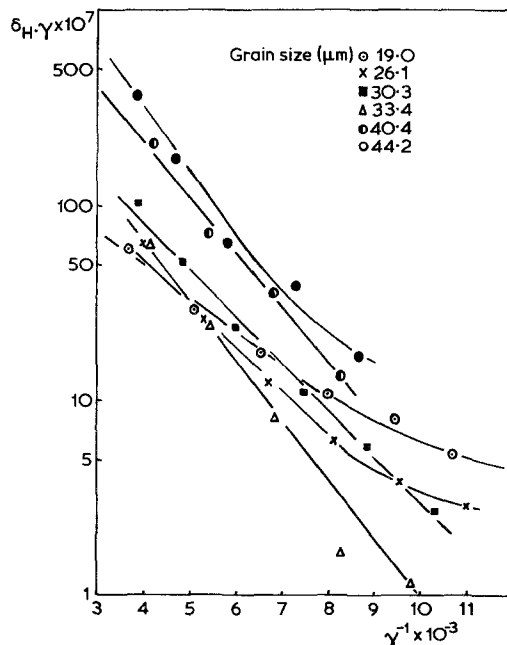


Figure 7 Granato-Lücke plots at 226 K.

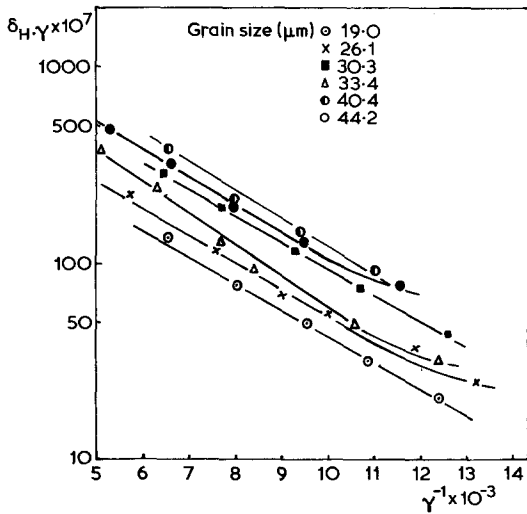


Figure 8 Granato-Lücke plots at 294 K.

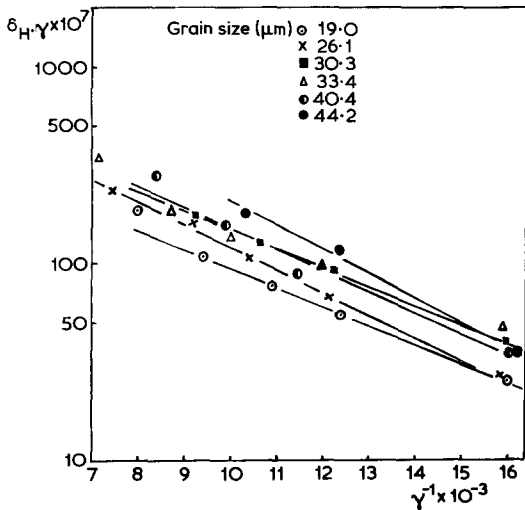


Figure 9 Granato-Lücke plots at 334 K.

and 334 K. The slopes have been calculated and are given in Table I.

As the grain size increases there is a general increase in the slopes at all temperatures. Thus as the grain size increases the loop length L_c decreases indicating a movement of solute atoms to the dislocations.

4. Discussion

As the grain size increases there is a movement of solute atoms to the dislocations. This solute must come from either the lattice or grain boundaries, or both. As the grain size increases the total volume of grain boundaries decreases and the volume of the lattice increases. Therefore if the

concentration of solute at the grain boundaries is to remain approximately constant (from the Arrhenius equation $C_g = C_L e^{H_g/RT}$, where C_g and C_L are the solute concentrations at the grain-boundary and in the lattice respectively) then as the volume of grain-boundary decreases, solute must enter the lattice.

This increase in the lattice concentration will produce an increase in the solute concentration at the dislocations through a similar Arrhenius equation, and hence reduces the loop length L_c .

It is also possible to obtain a quantitative explanation of these results as follows. If n_L and n_g are the total number of solute atoms within the grain and at the grain-boundary respectively then

$$\frac{\partial n_L}{\partial d} + \frac{\partial n_g}{\partial d} = 0 \quad (1)$$

where d is the grain diameter. If the concentration of the solute in the grain and at the grain-boundary is C_L and C_g respectively then

$$C_L = \frac{n_L}{N_L}; \quad C_g = \frac{n_g}{N_g} \quad (2)$$

where N_L and N_g are the total number of atoms within the grain and at the grain-boundary. Equation 2 then becomes

$$\left. \begin{aligned} \frac{\partial n_L}{\partial d} &= C_L \frac{\partial N_L}{\partial d} + N_L \frac{\partial C_L}{\partial d} \\ \frac{\partial n_g}{\partial d} &= C_g \frac{\partial N_g}{\partial d} + N_g \frac{\partial C_g}{\partial d} \end{aligned} \right\} \quad (3)$$

It is assumed that the grains are spherical, having diameter d , and that the width of the grain boundary is W the volume of a grain is $\frac{4}{3}(\pi d^3/8)$ and $N_L = (\pi d^3/B)$ where B is the volume per atom. Also $N_g = \pi d^2 W/B$. Equation 3 can be rewritten:

$$\left. \begin{aligned} \frac{\partial n_L}{\partial d} &= C_L \frac{\pi d^2}{2B} + \frac{\pi d^3}{6B} \frac{\partial C_L}{\partial d} \\ \frac{\partial n_g}{\partial d} &= C_g 2\pi d \frac{W}{B} + \pi d^2 \frac{W}{B} \frac{\partial C_g}{\partial d} \end{aligned} \right\} \quad (4)$$

Inserting Equation 4 into Equation 1:

$$C_L \frac{\pi d^2}{2B} + \frac{\pi d^3}{6B} \frac{\partial C_L}{\partial d} = - \left[C_g 2\pi d \frac{W}{B} + \pi d^2 \frac{W}{B} \frac{\partial C_g}{\partial d} \right] \quad (5)$$

Now,

$$C_g = C_L \exp [H_g/RT] \quad (6)$$

where H_g is the binding energy of the solute atom to the grain-boundary. Equation 5 becomes

$$C_L \frac{d}{2} + \frac{d^2}{6} \frac{\partial C_L}{\partial d} = - \left[C_L \exp(H_g/RT) \cdot 2W + dW \cdot \frac{\partial C_L}{\partial d} \cdot \exp(H_g/RT) \right] \quad (7)$$

Rearranging equation (7)

$$\begin{aligned} & C_L [d/2 + 2W \exp(H_g/RT)] \\ &= - \frac{\partial C_L}{\partial d} \left[wd \exp(H_g/RT) + d^2/6 \right] \\ \frac{1}{C_L} \frac{\partial C_L}{\partial d} &= - \left[\frac{(d/2 + 2W \exp(H_g/RT))}{(d^2/6) + Wd \exp(H_g/RT)} \right] \\ &= - \frac{1}{6} \left[\frac{1}{(d/6) + W \exp(H_g/RT)} \right] - \frac{2}{d} \\ \ln C_L &= - \ln [d/6 + W \exp(H_g/RT)] \\ &\quad - 2 \ln d + \text{constant} \\ \frac{\text{constant}}{C_L d^2} &= \frac{d}{6} + W \exp(H_g/RT). \quad (8) \end{aligned}$$

Now the concentration of solute on the dislocations is related to the concentration in the lattice through the equation

$$C_D = C_L \exp(H_D/RT)$$

where H_D is the interaction energy between the solute and the dislocation, Equation (8) becomes

$$\frac{\text{constant}}{C_D d^2 \exp(-H_D/RT)} = d/6 + W \exp(H_g/RT). \quad (9)$$

The change in loop length due to an increased solute concentration at the dislocation is given by

$$\frac{1}{L_c} = \frac{C_D}{a} \quad (10)$$

where a is the lattice parameter.

Combining Equations (9) and (10)

$$\frac{\text{constant}}{a \exp(-H_D/RT) d^2 \frac{1}{L_c}} = d/6 + W \exp(H_g/RT). \quad (11)$$

Now L_c^{-1} is proportional to the slopes of the Granato-Lücke plots and the values are given in Table I. Let the value of these Granato-Lücke slopes be Y , then Equation 11 can, therefore, be written as

$$\frac{\text{const.} \exp(H_D/RT)}{d^2 Y} = d/6 + W \exp(H_g/RT). \quad (12)$$

$[d^2 Y]^{-1}$ is plotted against d in Fig. 10 for the temperatures 226, 294 and 334K. The plots are linear at the larger grain sizes. At grain sizes below $28 \mu\text{m}$ the ordinate values increase at a faster rate. This may be due to the approximations involved in the theory. For example grains are never spherical and the smaller the grain size the greater is the error due to any deviation from a sphericity.

From Equation 12

$$\begin{aligned} \text{const.} [d^2 Y]^{-1} &= d/6 \exp(-H_D/RT) \\ &\quad + W \exp(H_g/RT). \end{aligned}$$

The slopes of the lines in Fig. 10 should be proportional to $\exp H_D/RT$. A plot of the logarithm

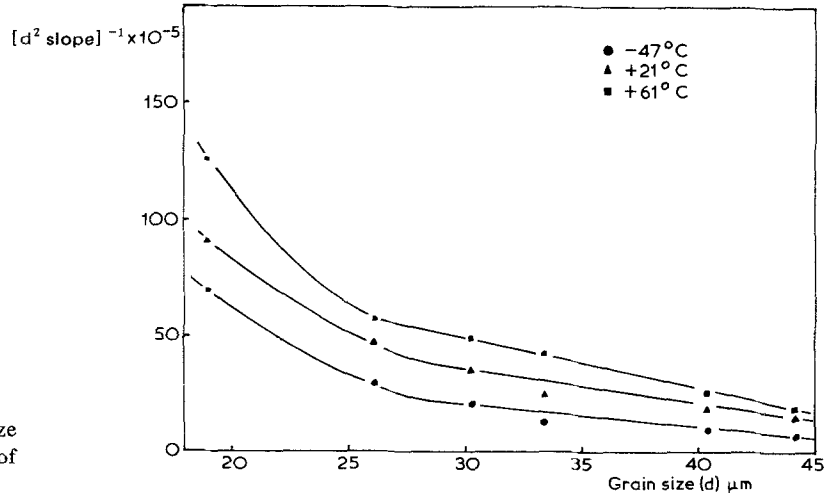


Figure 10 Reciprocal of grain size squared multiplied by slope of $G-L$ plots versus grain size.

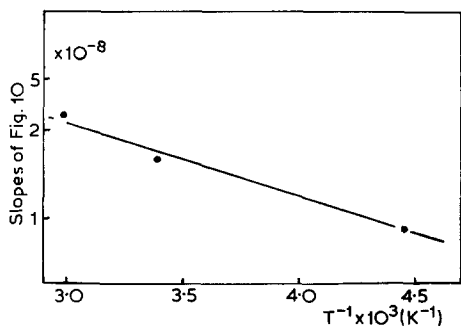


Figure 11 Slope of linear plots of Fig. 10 versus T^{-1} .

of the slopes versus T^{-1} should yield a value for the binding energy of a solute atom, most possibly lead or cadmium, to a dislocation in zinc. This is shown in Fig. 11 from which an activation energy of 0.05 eV has been calculated.

Theoretical binding energies for lead and cadmium atoms to dislocations in zinc have been computed to be 0.15 and 0.06 eV respectively using the Cottrell–Bilby equation [5].

5. Conclusions

The change in background damping near to the grain-boundary peak temperature in zinc, due to

a change in grain size has been explained in terms of a redistribution of solute. Thus as the grain size increases there is a movement of solute atoms to the dislocations. This reduces the dislocation loop length and the internal friction. A simplified model has been developed and this leads to solute-dislocation binding energy of approximately 0.05 eV.

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