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Dislocation damping and associated modulus defect in copper crystals

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Abstract

Ultrasonic attenuation and the modulus defect were investigated in ⟨111⟩-deformed copper single crystals. Experimental results were interpreted as resulting from the contribution of two dislocation mechanisms: kink resonance and kink relaxation (stress-induced double-kink formation). Bordoni peak relaxation is described considering no distribution in activation energy or relaxation time. The kink density contributing to the resonance mechanism is shown to be dependent on temperature.

1. Introduction

The ultrasonic attenuation and the associated modulus defect in high purity metals are caused mainly by the presence of dislocations [1, 2]. In deformed f.c.c. crystals a relaxation peak, called the Bordoni peak (BP), has been observed [2–4]. The BP was extensively investigated at low frequencies and its primary characteristics are well established [2]. Secondary characteristics, such as the width, are not well understood yet.

Measurements in the megahertz range have the advantage of enabling us to investigate the same sample at different frequencies. Mongy *et al.* [5] reported an orientation anisotropy for the peak temperature, which was not confirmed by other authors [6, 7]. However, ultrasonic attenuation measurements alone cannot adequately help to explain the BP width, owing to the concurrence of more than one dislocation mechanism contributing to the damping. Simultaneous measurements of ultrasonic attenuation and velocity [7] appeared to be helpful for obtaining additional information about the Bordoni relaxation.

This study deals with the interpretation of results obtained for the logarithmic decrement δ and modulus defect $\Delta M/M_0$ in deformed copper single crystals. A solution is proposed which separates the contributions of kink resonance and Bordoni relaxation to the dislocation damping and modulus defect.

2. Experimental procedure

High purity copper single crystals (residual resistivity ratio (RRR) $\approx$ 1500) in the form of cubes of side 1 cm were used as samples in this work. The specimens, previously oriented by the Laue X-ray method, were deformed by compression in the ⟨111⟩ direction. The samples were left for 1 h at 373 K after the deformation.

Ultrasonic attenuation and velocity were measured simultaneously using the pulse echo method [8]. The time for a round trip pulse on the sample was obtained by the pulse echo overlap technique [9].

Measurements were performed while cooling the samples between 300 and 80 K at a rate of 1 K min^{-1}. In an undeformed sample, irradiated with γ-rays until total pinning of the dislocations occurred, we measured the dislocation-free ultrasonic attenuation α_i and velocity v_0 (background). The background, and its temperature dependence, were assumed to be the same for all investigated samples.

The logarithmic decrement δ and the modulus defect $\Delta M/M_0$ were calculated as reported in ref. 7.

3. Results and discussion

Figures 1 and 2 show typical temperature dependences for the logarithmic decrement and modulus defect of the investigated samples. The δ curves present a peak (at 172 K and at 153 K in Fig. 1(a) and Fig. 2(a) respectively), which is well known as the BP [1–4]. In

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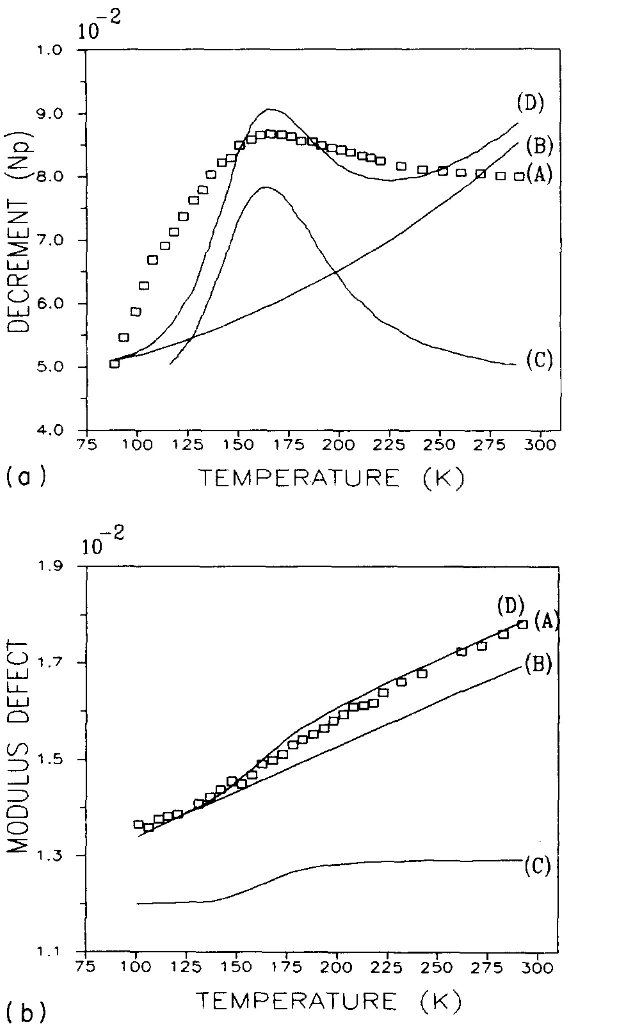

Fig. 1. Temperature dependence of (a) the logarithmic decrement and (b) the modulus defect for a 3%-⟨111⟩-deformed copper crystal, measured at 50 MHz with a ⟨111⟩ longitudinal wave: curves A, experimental results; curves B, kink resonance contribution; curves C, Bordoni relaxation; curves D, calculated total values.

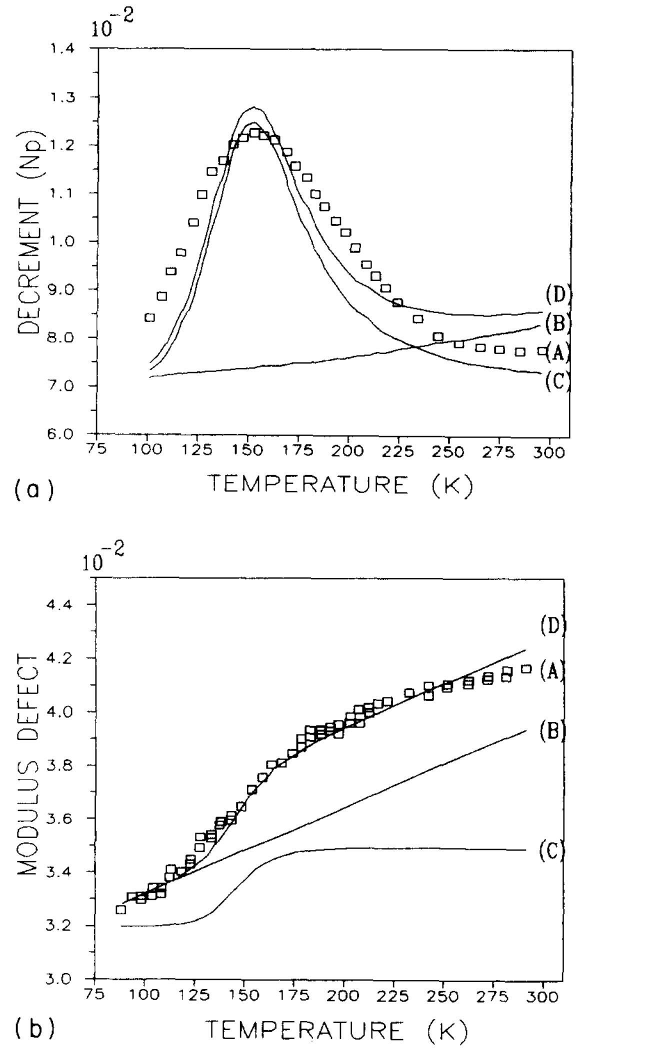

Fig. 2. Temperature dependence of (a) the logarithmic decrement and (b) the modulus defect for a 10%-⟨111⟩-deformed copper crystal, measured at 30 MHz with a ⟨111⟩ longitudinal wave: curves A, experimental results; curves B, kink resonance contribution; curves C, Bordoni relaxation; curves D, calculated total values.

the BP region the modulus defect exhibits a pronounced step (Figs. 1(b) and 2(b)), previously reported and related to the Bordoni relaxation mechanism [7]. Figures 1(b) and 2(b) also show a decrease of $\Delta M/M_0$ with increasing temperature, on the high temperature side of the BP. At room temperature the modulus defect presented no frequency dependence.

To explain our experimental results for $(\Delta M/M_0)(T)$ and $\delta(T)$ we propose a summation of two contributions: (1) overdamped resonance of kinks [8, 10] and (2) Bordoni relaxation (stress-induced kink pair formation) [8, 11]. We consider the following equations:

$$\begin{aligned}(\Delta M/M_0)(T) &= (\Delta M/M_0)_B + (\Delta M/M_0)_{res}\\ &\propto \Delta_B/[1+(\omega\tau)^2] + N(T)L^2\\ &= \Delta_B/[1+(\omega\tau)^2] + A_1 T + (\Delta M/M_0)_{77\ K}\end{aligned} \tag{1}$$

$$\begin{aligned}\delta(T) &= \delta_B + \delta_{res}\\ &\propto \Delta_B\omega\tau/[1+(\omega\tau)^2] + N(T)L^4\omega B(T)\\ &= \Delta_B\omega\tau/[1+(\omega\tau)_2]A_2T^2 + \delta_{77\ K}\end{aligned} \tag{2}$$

where Δ_B is the relaxation strength for Bordoni relaxation; $\tau = \tau_0 \exp(E/kT)$ is the relaxation time for Bordoni relaxation; E is the activation energy; A_1 and A_2 are characteristic constants of the material and dislocation structure; $N(T) \propto T$ is the kink density; L is the dislocation loop length; $B(T) \propto T$ is the damping coefficient, due to the dislocation–phonon interaction; and ω is the angular frequency.

Because the modulus defect is not frequency dependent at room temperature, we might suppose we are in the low-frequency range of the kink resonance mechanism [8, 10]. A kink density varying linearly with the temperature was assumed. Because the damping coefficient $B(T)$, due to the interaction between dislocations and phonons, also varies linearly with temperature [12], the term δ_{res} was considered proportional to T^2.

The Bordoni relaxation contribution ($(\Delta M/M_0)_B$, δ_B) is described as a single Debye relaxation. No kink diffusion was considered. An activation energy of 0.12 eV, obtained in an Arrhenius plot using the most representative experimental results [2], was used for the fitting.

To fit the experimental results, considering eqns. (1) and (2), we used the Levensberg–Marquardt method [13]. We assumed that at 77 K $\Delta M/M_0$ and δ were associated only with the two mechanisms described above. This cannot be totally correct if we also have the contribution of the Niblett–Wilks peak [2]. By fitting the modulus defect results, Δ_B and A_1 were determined. The experimental $\delta(T)$ results were fitted using the Δ_B values obtained from the modulus defect curves.

A comparison between experimental results (curve A) and theoretical results (from the fitting, curves D) is shown in Figs. 1 and 2. As can be seen in Figs. 1(b) and 2(b) a very good agreement for theoretical and experimental values is achieved for $\Delta M/M_0$ with our proposal. For the logarithmic decrement the fitting was better for the more deformed sample (Figs. 1(a) and 2(a)). The discrepancies observed in the less deformed samples are believed to be due to the following: (a) at high temperatures the logarithmic decrement in deformed samples cannot be well described by the kink resonance or string models [12]; (b) at temperatures lower than 220 K stresses can be generated due to the difference in expansion coefficients between the crystals and the transducer. Less deformed samples have longer dislocation loop lengths so that they should be more sensitive to these stresses.

Figures 1 and 2 also present the contribution related to resonance (curves B) and relaxation (curves C) of kinks. Because of our assumption of only one activation energy and relaxation time the calculated BP is a simple Debye peak. The width of this peak represents half of the "effective width" (1.9–2.2) obtained directly from the experimental results [7]. So, in our assumption, the effective peak broadening would be caused mainly by the contribution of the overdamped kink resonance.

4. Conclusions

The ultrasonic attenuation and modulus defect due to dislocations were investigated in copper single crystals, deformed in the ⟨111⟩ direction. The experimental results can be well fitted considering the contribution of two dislocation mechanisms: overdamped kink resonance and kink relaxation (responsible for the BP). The Bordoni relaxation is described assuming only one activation energy and relaxation time τ_0 (obtained from an Arrhenius plot). After our analysis, a BP width results, which is nearly half of that obtained directly from the experimental data [7]. The kink resonance contribution considers a kink density that depends on temperature.

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