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Study of the dislocation relaxation peaks in easy glide deformed silver single crystals having different length-to-width ratios

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Abstract

The dislocation relaxation peaks in a deformed silver single crystal of orientation ⟨110⟩, *i.e.* easy glide, with length-to-width ratios of 8:1, 6.5:1, 4.9:1, 4:1 and 1:1 have been studied. These relaxation peaks have been measured at frequencies of 5, 10 and 30 MHz. The results showed that a crystal with the ratio 8:1 produced the highest dislocation relaxation peaks at higher temperature. As the ratio decreased, the peak height decreased nearly linearly when the measurements were carried out at 5 MHz. At frequencies of 10 and 30 MHz, the peak height fell dramatically, especially for ratios less than 8:1. The large dislocation relaxation peak height which occurred at higher temperature in the sample of ratio 8:1 was attributed to long dislocation loops formed during deformation. These loops seem to become shorter as the length-to-width ratio decreases.

1. Introduction

According to Kocks *et al.* [1], deformation in uniaxial compression does not necessarily give the same result as deformation in uniaxial tension, essentially because the boundary conditions chosen are almost always different. This is because the shape and size of the specimen are usually different, and any genuine effect of size on work hardening should thus influence the result. Furthermore, they reported that as the ratio of length to width (from 8:1 to 1:1 in Al, Ag and Au samples) decreases, the amount of easy glide decreases until it is entirely absent. Since the dislocation relaxation peak (*i.e.* Bordoni peak) [2] only occurs after the sample has been deformed plastically [3], and its relaxation magnitude (peak height) is dependent on the dislocation loop length caused by deformation [4], we thought it important to study the effect of deforming silver samples of orientation ⟨110⟩ (*i.e.* easy glide), having different length-to-width (diameter) ratios, on the magnitude and the peak temperature of the dislocation relaxation peak. This is important to know, especially if one wants to calculate the activation enthalpy of the relaxation process from the Arrhenius graph (plot of logarithmic frequency *vs.* the reciprocal $1/T_m$ of the peak temperature) taking into consideration only sample impurity, deformation (amount, type and temperature), orientation, and others but ignoring the dimension of the sample (*i.e.* ratio of length to width).

2. Experimental procedures

A long cylindrical bar of very high purity (99.9999%) and of length 10.4 mm and diameter 13 mm (*i.e.* length-to-width ratio 8:1) was supplied by Goodfellow Company. The crystal was given a force of 1000 N and the resulting resolved shear stress (RSS) was 3.7 MPa. The ultrasonic attenuation was measured using the single-ended pulse echo technique as frequencies of 5 ,10 and 30 MHz [5] from liquid nitrogen temperature to room temperature. The sample was then cut using a Buchler low speed diamond saw to give a ratio of 6.5:1, and then annealed at 750 °C for 4 h in argon gas. The specimen was then given a force of 1000 N (*i.e.* RSS, 3.7 MPa) and again the ultrasonic attenuation at three frequencies, 5, 10 and 30 MHz, from liquid nitrogen to room temperature was measured. Afterwards the samples were cut to have ratios of 4.88:1, 4:1, and 1:1 where procedures similar to that described above were carried out between each ratio.

The orientation was checked at each ratio by the Laue back reflection X-ray method and the orientation was within 3° of the appropriate axis. The specimens were left for 3 days at room temperature after deformation before the ultrasonic attenuation was measured, in order to eliminate the Koster effect [6].

3. Results and discussion

Figure 1(a), 1(b) and 1(c) show the dislocation relaxation peaks measured at frequencies of

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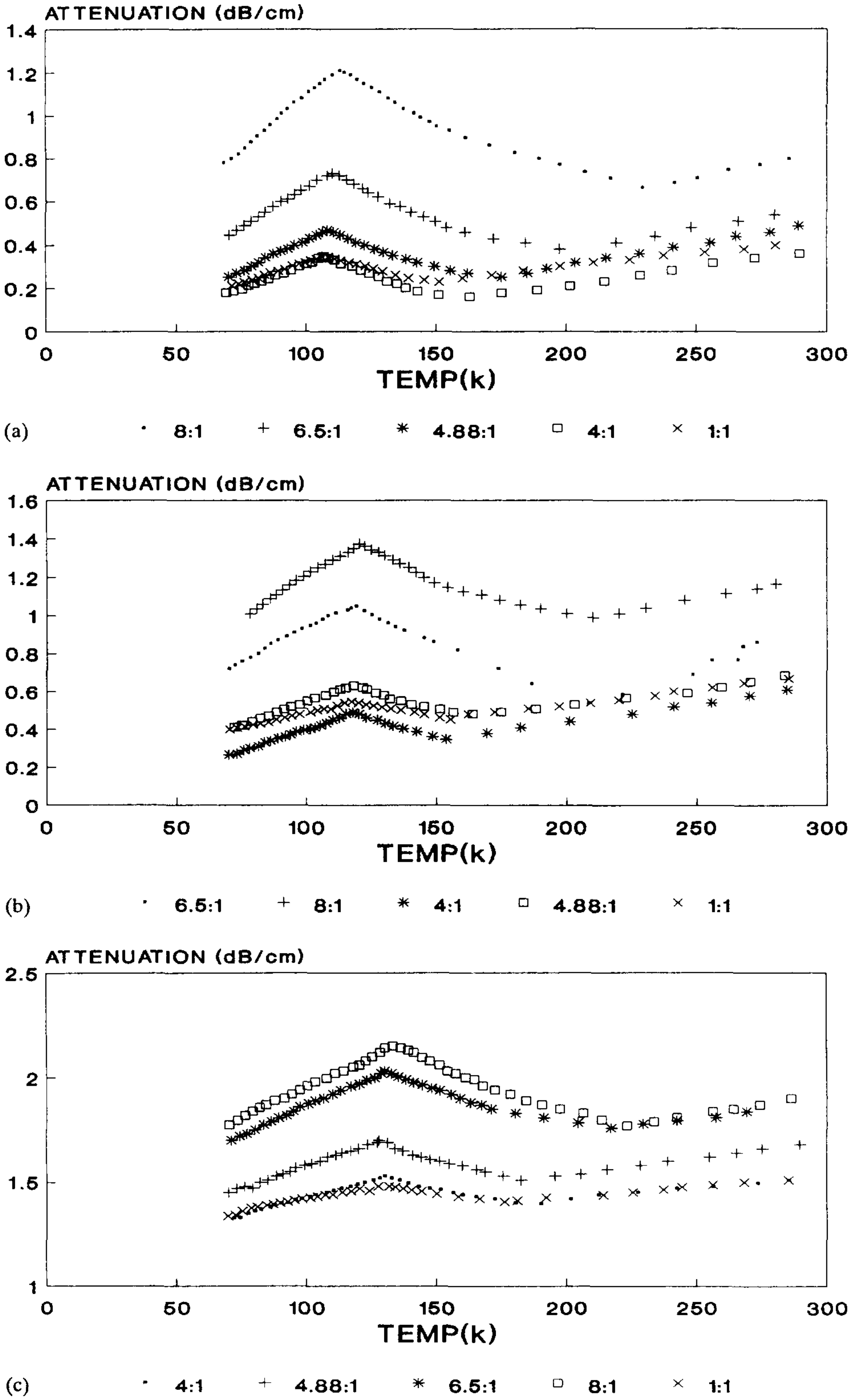

Fig. 1. The ultrasonic attenuation of ⟨110⟩ silver crystals having different length-to-width ratios as a function of temperature at different frequencies: (a) 5 MHz; (b) 10 MHz; (c) 30 MHz.

5 MHz, 10 MHz and 30 MHz respectively in high purity silver single crystals having orientation ⟨110⟩ and different length-to-width ratios. At all frequencies the maximum damping Q_{max}^{-1} is largest in samples having 8:1 ratio and least for the 1:1 ratio.

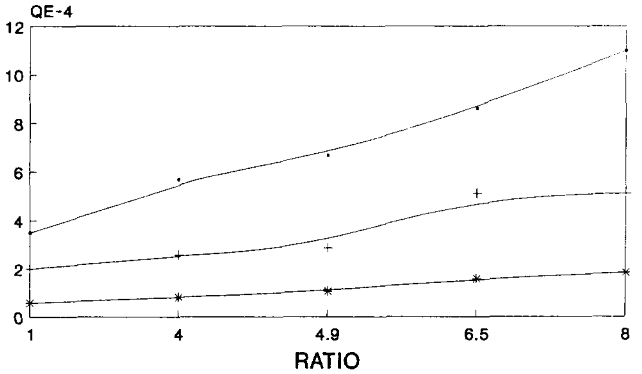

Fig. 2. The variation in dislocation relaxation peak height with length-to-width ratio measured at various frequencies (5, 10 and 30 MHz).

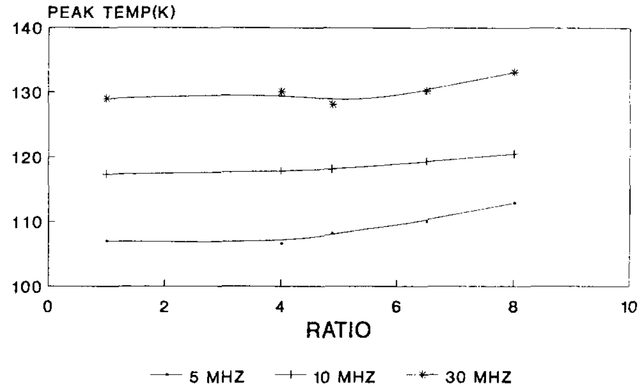

Fig. 3. The variation in the dislocation relaxation peak temperature with length-to-width ratio measured at different frequencies (5, 10 and 30 MHz).

Figure 2 shows the behaviour of Q_{max}^{-1} with different length-to-width ratios measured at different frequencies for samples given a similar amount of RSS (3.7 MPa). The reduction in the peak height as the length-to-width ratio decreases is nearly linear in all samples, but the largest slope is found for results at 5 MHz, followed by 10 MHz and 30 MHz. This indicates that the interaction of the applied frequency f with the dislocation loop length may be important.

Esnouf and Fantozzi [7] applied the rate theory to kink pair relaxation for a many-valley periodic potential and found for the case of heavily deformed samples that the relaxation decrement d of the Bordoni peak ($\delta = \pi Q_{max}^{-1}$) decreases with the frequency f according to the relation

$$\delta = \delta_1(1-0.04)\ \ln f \qquad (1)$$

where δ_1 is the peak decrement at a frequency of 1 Hz. This is in agreement with our results, shown in Fig. 2, which indicate that for a particular ratio the peak height at higher frequencies (30 MHz) is lower than those measured at lower frequencies (5 MHz).

For the purpose of estimating the Bordoni peak height Q_{max}^{-1} at a particular length-to-width ratio R (from 8:1 to 1:1) at frequencies of 5, 10 and 30 MHz for inclusion in the Arrhenius plot, we found the following correlations:

$$Q_{max}^{-1} = 1.926\times10^{-2} + 1.059\times10^{-2}R \ (f=5 \text{ MHz}),\quad r=0.9834 \qquad (2)$$

$$Q_{max}^{-1} = 1.050\times10^{-2} + 5.075\times10^{-3}R \ (f=10 \text{ MHz}),\quad r=0.9106 \qquad (3)$$

$$Q_{max}^{-1} = 2.42\times10^{-3} + 1.91\times10^{-3}R \ (f=30 \text{ MHz}),\quad r=0.9588 \qquad (4)$$

Figure 3 shows the variation in the peak temperature as the ratio of length to width changes. As the ratio decreases, the peak temperature decreases also for all three frequencies (*i.e.* 5, 10 and 30 MHz). The figure also shows that as the frequency increases the peak temperature shifts to higher temperature for a particular length-to-width ratio. This behaviour has been found in different materials measured in our laboratory [8–10].

The following correlations were found between the Bordoni peak (dislocation relaxation peak) temperature T_m and the length-to-width ratio R at different frequencies:

$$T_m = 1.048\times10^2 + 0.845R \ (f=5 \text{ MHz}),\quad r=0.8661 \qquad (5)$$

$$T_m = 1.164\times10^3 + 0.455R \ (f=10 \text{ MHz}),\quad r=0.9325 \qquad (6)$$

$$T_m = 1.277\times10^2 + 0.448R \ (f=30 \text{ MHz}),\quad r=0.6867 \qquad (7)$$

Clearly, the correlation coefficients r for the above relations (eqns. (5)–(7)) are less than those found for Q_{max}^{-1} *vs.* R (eqns. (2)–(4)).

Figure 4 shows the relation between Q_{max}^{-1} and T_m *vs.* R at frequencies of 5, 10 and 30 MHz. The following correlations were found between these three variables:

$$R = 50.646 + 13\,457.84Q_{max}^{-1} - 0.508T_m \ (f=5 \text{ MHz}),\quad r=0.9979 \qquad (8)$$

$$R = -160.592 + 4952.978Q_{max}^{-1} - 01.38T_m \ (\text{f}=10 \text{ MHz}),\quad r=0.9372 \qquad (9)$$

$$R = 8.932 + 50\,154.98Q_{max}^{-1} - 0.076T_m \ (f=30 \text{ MHz}),\quad r=0.09595 \qquad (10)$$

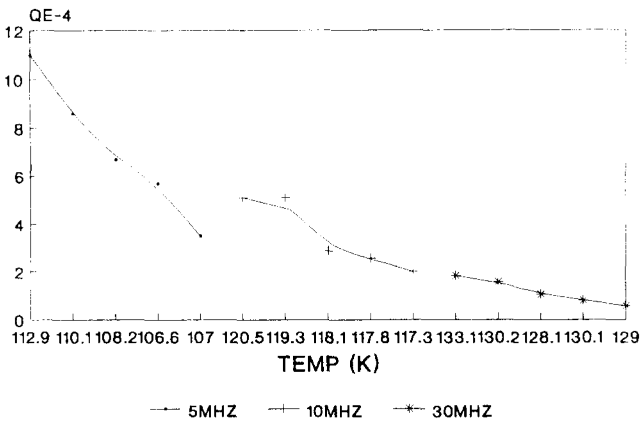

Fig. 4. The variation in the dislocation relaxation peak height and temperature for silver single crystals having different length-to-width ratios measured at three frequencies 5, 10 and 30 MHz). The point at the top of each curve is for the 8:1 ratio and that at the bottom is for the 1:1 ratio.

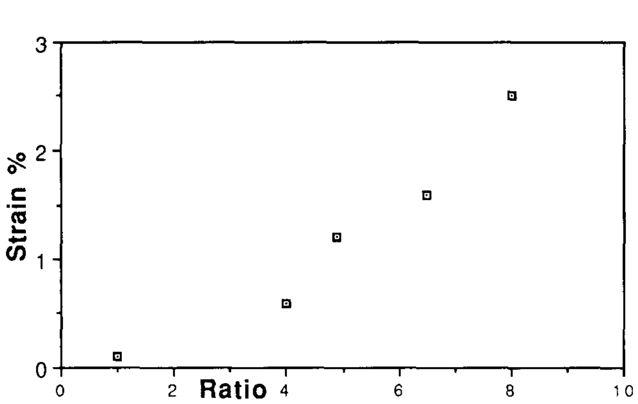

Fig. 5. The relation between the strain and the length-to-width ratio for ⟨110⟩ silver single crystals having an RSS of 37 MPa.

In correlating four variables together, *i.e.* f, T_m, R and Q_{max}^{-1}, we found that the correlation coefficient r becomes less, *i.e.*

$$R = -41.406 + 8359.6 Q_{max}^{-1} + 0.376 T_m - 0.119 f, \quad r = 0.8446 \qquad (11)$$

In fact the presence of a large Bordoni peak in the compressed samples of ⟨110⟩ orientation with a length-to-width ratio of 8:1 suggests that it is associated with easy glide. It also proves that the Bordoni peak is formed by a thermally activated relaxation process involving dislocations (screw dislocations) lying parallel to a close-packed direction in the crystal lattice [11–12]. This is justified by the intersection of screw dislocations which may be the most important mechanism of hardening in the easy glide region [13].

It is expected from the work of Kocks *et al.* [1], who attributed the absence of easy glide as the length-to-width ratio decreases (as shown in Fig. 5) to the association of the easy glide with heterogeneous deformation, that a large number of long dislocation loops parallel to the close-packed direction are responsible for the large Bordoni peak in samples exhibiting easy glide. The peaks occur at higher temperature and have relatively high background damping on the high temperature side of the peak.

The association of higher peak temperature with higher length-to-width ratio, and their reduction as the ratio decreases, may be explained by the Paré condition [14]:

$$\sigma_i l a b \geqslant W \qquad (12)$$

where W is the activation enthalpy for formation of a pair of kinks, l is the free loop length, σ_i is the internal stress, a the atomic distance, and b is the Burgers vector. The term, $\sigma_i l a b$ is the work done in moving the dislocation loop length from the straight to the deformed position. Since W is related to T_m ($f = f_0 e^{-W/kT}$; f_0 is the attempt frequency) then it is expected that the dislocation loop length becomes shorter. This may be due to heterogeneous deformation or dislocation–dislocation interaction. Hence W and accordingly T_m will shift to lower temperatures.

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