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Effect of pre-strain on the dislocation relaxation in zinc single crystal

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The ultrasonic absorption, α, in a zinc single crystal was measured as a function of temperature along three different orientations. The effect of different amounts of pre-strain on the absorption is investigated. It has been found that the energy, W, activating the relaxation process is independent of the amount of pre-strain, while the attempt frequency, ν_0, and the temperature of the absorption peak, T_m, are pre-strain dependent. The relaxation strength indicates a slight maximum in the considered range of pre-strain. Seeger theory has been used to explain some features of the experimental data, however, all the existing theories fail to explain the dependence of the parameters W and ν_0 on the orientation.

1. Introduction

Extensive studies of Bordoni peaks have been carried out by numerous investigators [1–3]. It has been established that the peak is due to the relaxation processes that involve dislocations. Yet there is some doubt about the dislocation mechanisms which are responsible for the internal friction peak. Mason [4] assumed that the jumping of dislocations parallel to close-packed directions between two adjacent positions of energy minimum is responsible for the relaxation process. Seeger and Schiller [5, 6] on the other hand assumed that the relaxation processes involve the displacement of kinks in the dislocations rather than long segments extended between strong pinning points. The kink assumes a certain width, W, and the separation between kinks depends on the applied stress. Seeger theory [5], though, accounts for some features yet fails to predict some others.

In contrast to the Seeger [5] assumption of creation and annihilation of the kinks, Brailsford [7] proposed relaxation of inherently kinked dislocations whose average direction is different from the close-packed direction. The effect of stress is to redistribute the abrupt kinks. The model predicts the right values of both activation energy and the peak width, but the anisotropy effect, namely, the dependence of the activation energy, W, and the temperature of the peak maximum on the orientation, were not considered by any of the existing theories. By two of the authors [8], a high degree of anisotropy is observed in the values of the activation energies and relaxation frequencies when measurements are made in different orientations for zinc single crystal.

It has been assumed that the frequency, ν, and the temperature, t_m, of the peak heights satisfy a relation of the form $\nu = \nu_0 \exp(-W/kT_m)$ where ν_0 is some intrinsic parameter, irrespective of the nature and amount of pre-strain. This has not been always the case, there appear to be no universally [9] accepted values of W and ν_0. Niblett and Wilks [10] suggested that since the peak temperature is a function of the nature and amount of pre-strain, a better way to determine these parameters is to consider only data from specimens deformed in the same manner by comparable amounts of pre-strain.

Following this suggestion, the absorption of ultrasonic waves by a zinc single crystal subjected to different amounts of pre-strain along the [0001] direction is investigated. The effect of applying systematic pre-strain on the relaxation phenomena and the associated parameters are discussed in terms of the existing theoretical models.

2. Experimental details

The zinc single crystal, under test, is enclosed in a cryostat which can be adjusted to the desired temperature by the aid of liquid nitrogen. The temperature is measured by a calibrated copper–constantan thermojunction, in close contact with the crystal, to an accuracy of 1 K. The specimen of purity 99.995 %, in the form of a cube of side about 20 mm was orientated within 1° parallel to the crystallographic directions [0001], $[\bar{1}0\bar{1}0]$ and $[12\bar{1}0]$. The crystal was annealed for 5 h at a temperature of 450 K. The sample was then pre-strained along [0001] direction by the amounts 0.5, 1.5, 3.0, 5.0 and 8.0%. The ultrasonic pulse echo technique was used to measure the attenuation of longitudinal ultrasonic waves at frequencies 3.0, 4.2, 6.0 and 9.0 MHz in the temperature range of 80 to 300 K. The glass solution was used as a bonding medium between the quartz crystal (tranducer) and the specimen. The standard deviation in calculating the absolute values of α is given by $\pm$ 10%, but the error in relative measurements does not exceed 1%.

3. Results

The attenuation of longitudinal ultrasonic waves of zinc single crystal subjected to different amounts of pre-strains is measured as a function of temperature. The results are shown in Figs 1a–c, 2a–c and 3a–c for

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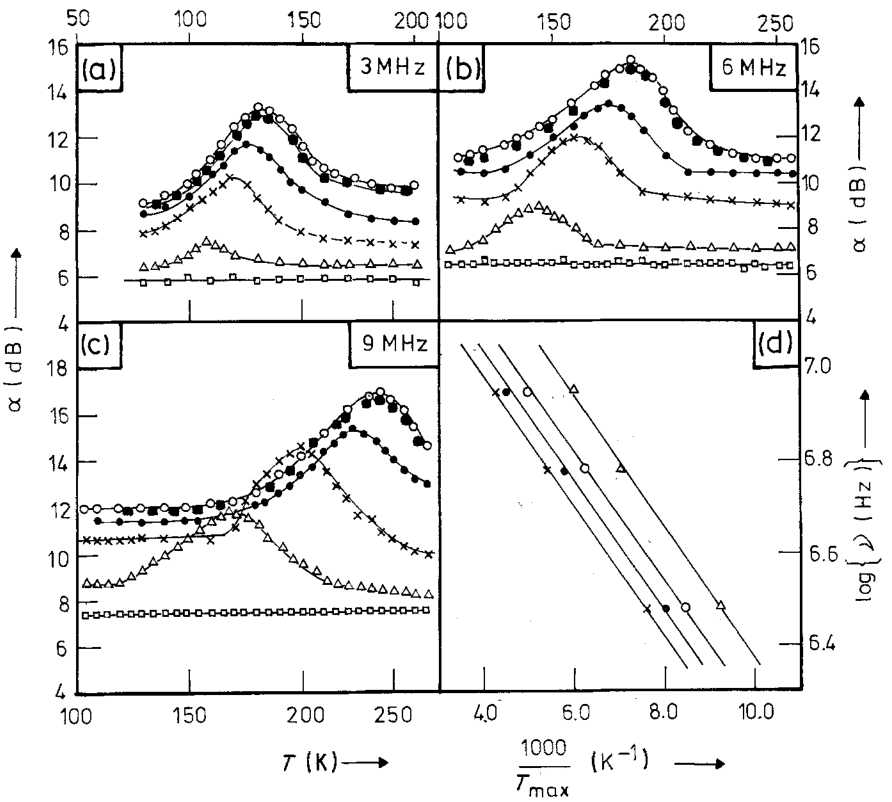

Figure 1 (a), (b) and (c) The effect of pre-strain on the relaxation peak of zinc single crystal [0 0 0 1] at several frequencies. (□) Annealed, (△) 0.5%, (x) 1.5%, (○) 3%, (■) 5% and (●) 8%. (d) The linear relation between log ν and $1/T_{max}$ for different values of pre-strain. (△) 0.5%, (○) 1.5%, (●) 8%, (x) 3 and 5%.

the three different orientations [0 0 0 1], [1 0 $\bar{1}$ 0] and [$\bar{1}$ 2 $\bar{1}$ 0]. The data points are collected at the frequencies 3.0, 4.2, 6.0 and 9.0 MHz. It is evident from these figures that

1. The peaks are shifted to higher temperatures when measurements are made at higher frequencies. The value of the activation energy, W, as obtained from Figs 1d, 2d and 3d is independent of the amount of pre-strain. However, its value is orientation dependent, namely, 0.028 eV for [1 0 $\bar{1}$ 0], 0.03 eV for [$\bar{1}$ 2 $\bar{1}$ 0] and 0.10 eV for [0 0 0 1] orientation.

2. The relaxation strength increases monotonically with pre-strain up to about 3% pre-strain. When the pre-strain is increased further the relaxation strength seems to pass through a slight maximum, this is shown in Fig. 4c.

3. For a fixed frequency the temperature at which the peak occurs shifts towards higher values with increasing amounts of pre-strain up to 3%. Thereafter the peak descends as shown in Fig. 4b; no dissipation peak has been observed when the sample is annealed for 5 h at a temperature of 450 K.

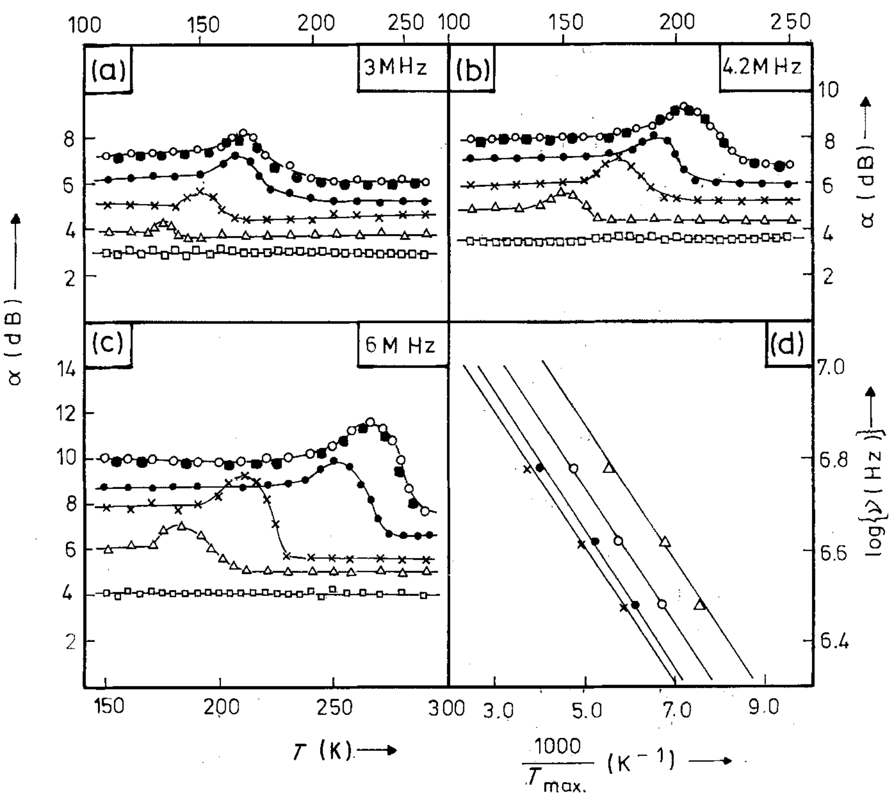

Figure 2 (a), (b) and (c) The effect of pre-strain on the relaxation peak of zinc single crystal [$\bar{1}$ 0 $\bar{1}$ 0] at several frequencies. (□) Annealed, (△) 0.5%, (x) 1.5%, (○) 3%, (■) 5% and (●) 8%. (d) The linear relation between log ν and $1/T_{max}$ for different values of pre-strain. (△) 0.5%, (○) 1.5%, (●) 8%, (x) 3 and 5%.

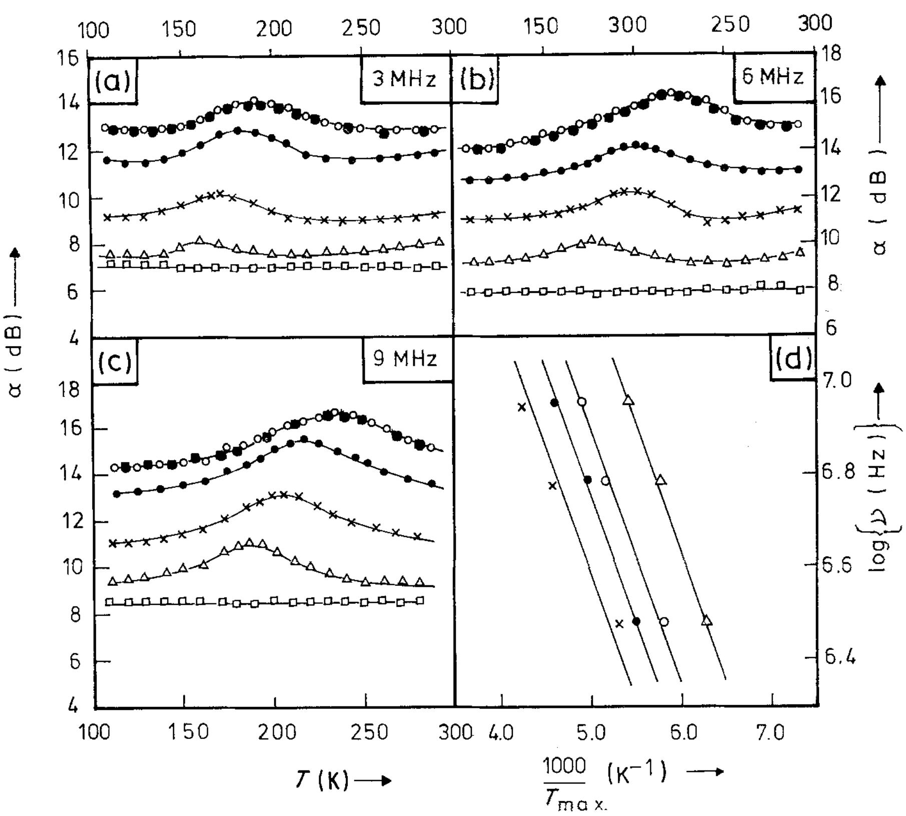

Figure 3 (a), (b) and (c) The effect of pre-strain on the relaxation peak of zinc single crystal [1 2 $\bar{1}$ 0] at several frequencies. (□) Annealed, (△) 0.5%, (x) 1.5%, (○) 3%, (■) 5% and (●) 8%. (d) The linear relation between log ν and $1/T_{max}$ for different values of pre-strain. (△) 0.5%, (○) 1.5%, (●) 8%, (x) 3 and 5%.

4. Discussion

The activation energy, W, is independent of the pre-strain, therefore, it is an intrinsic property of a dislocation line. It does depend, however, on the relative orientation of the Burger's vector and the direction of the dislocation line, since W is independent of dislocation density, thermally activated formation of pairs of kinks could account for the main features of the relaxation phenomena. The frequency, ν, of formation of pairs of kinks can be represented by:

$$\nu = \nu_0 \exp(-W/KT_m) \qquad (1)$$

However, the value of W is found to be a function of the orientation which is not taken into consideration by Equation 1. Also ν_0 which has been assumed to be a constant is found to depend on both pre-strains and orientation, Fig. 4a.

For a fixed frequency the temperature at which the peaks occur depends on the amount of pre-strain (see Fig. 4b). We found that the Bordoni peak that takes place at a temperature of 108 K for slightly deformed crystal of orientation [0 0 0 1] increases to 312 K as the compressional deformation is increased to 0.75 N mm^{-2}. Similar behaviour is observed for all the orientations. This is in contrast with the results obtained by Niblett and Zein [11] who observed a decrease of T_{max} with the increase of resolved shear stress. This indicates that the density of dislocation forest and the distance between dislocations are both important parameters. Therefore, the relaxation mechanisms are not only related to the intrinsic properties of dislocation, as has been always assumed, but also related to the presence of other dislocation lines. In fact the elastic interaction between dislocations is responsible for the slight maximum of the attenuation peak strength, as a function of pre-strain,

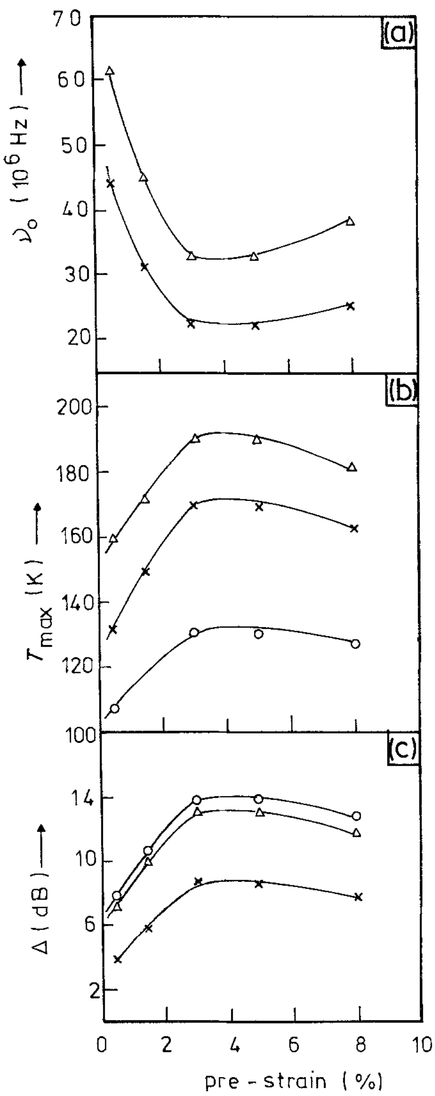

Figure 4 The effect of pre-strain on: (a) the attempt frequency; (b) the temperature of relaxation peak; (c) the relaxation peak strength.

Figs. 4c. According to Seeger [5], dislocation lines which on the average run parallel to one of the densely packed directions of the crystal contribute to the relaxation mechanism. However, the probability for a dislocation line to be along a close-packed orientation is small and therefore a small fraction of the dislocation density contributes to the relaxation mechanism. The total number of dislocations increases with increasing pre-strain. The number of dislocations along close-packed direction will increase with the increase of pre-strain up to about 3% pre-strain. When the pre-strain is increased further the average distance between dislocations gets smaller and elastic interactions tend to force the dislocations into some other directions leading to a decrease in the relaxation strength. Since the number of dislocations along the close-packed direction plays an important role in the relaxation mechanism, we cannot rule out the anisotropy effect which has been observed in this work. The absence of the Bordoni peak in annealed specimens corresponds to insufficient dislocation density. It also indicates that the interaction between dislocations and point defects has no significant effect on the observed peaks. In the presence of such interaction the peak amplitude of the Bordoni peak should increase upon annealing [3], a situation which has not been observed in our work.

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