

for the relaxation strength of the Bordoni peaks?

Gilman, J. J.: It is hard to guess what the effect of additional defects would be on the total concentration of dipole orientation junctions. However, additional defects would certainly be expected to decrease the number of mobile junctions because of elastic and chemical interactions.

PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON CRYSTAL LATTICE DEFECTS, 1962, SYMPOSIUM
JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 18, SUPPLEMENT I, 1963

Current Problem in the Theory of the Bordoni Relaxation

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The theory of the Bordoni relaxation based on the thermally activated formation of kink pairs is briefly reviewed. It is shown that a number of recent experiments, particularly after low temperature deformations, support the basic ideas of this theory. As a first approximation, the present theory appears to be satisfactory.

If a better approximation is attempted, a number of open questions exist. The most central one appears to be that of the width of the distribution of relaxation times observed experimentally. For f.c.c. metals, distributions in activation energies seem to be important. Significant differences, however, seem to exist between different crystal classes. Further problems are the variation of the peak shape with such treatments as neutron irradiation, annealing etc.

It is argued that some of these "secondary" features of the relaxation process may have to do with the migration of the kinks. It appears likely that a general theory of kink formation and migration will be able to solve the existing difficulties and to provide a unified picture for a wide class of internal friction phenomena associated with dislocation movements.

In 1955 the following explanation⁽³⁾⁻⁽⁵⁾ was proposed for the basic process of the mechanical low-temperature relaxation phenomenon first observed by Bordoni^{(1), (2)} in f.c.c. metals. Dislocation lines lying along crystallographic directions of high Peierls-stress (*e.g.* close-packed directions in the glide plane) form pairs of kinks under the combined action of thermal fluctuations and the applied shear stress. Short segments of the dislocation lines are thereby transferred from one Peierls valley to the neighbouring one (Fig. 1). This process is characterized by a time of relaxation (or by a spectrum of relaxation times). By a well-known argument, in an internal friction experiment a relaxation peak is observed. Dislocations with different character (*e.g.* screw dislocations or 60°-dislocations) may give rise to different relaxation peaks, and these were

tentatively identified with the proper Bordoni peak and the so-called N-W (Niblett and Wilks) peak⁽⁶⁾. Quantitative theoretical treatments of this relaxation process have been given later^{(7), (8)}.

The essential feature of the proposed relaxation mechanism is that it is an *intrinsic* dislocation process, *i.e.* that the relaxation time and its temperature variation depend only on the properties of the *individual* dislocations involved, and not on the interaction between different dislocation lines or between dislocations and point defects.

Since the above-mentioned interpretation was proposed, a large number of low-temperature internal friction studies have been performed on both metals and non-metals. These experiments are summarized by Niblett and Wilks⁽⁹⁾ and Sack⁽¹⁰⁾. In almost all materials

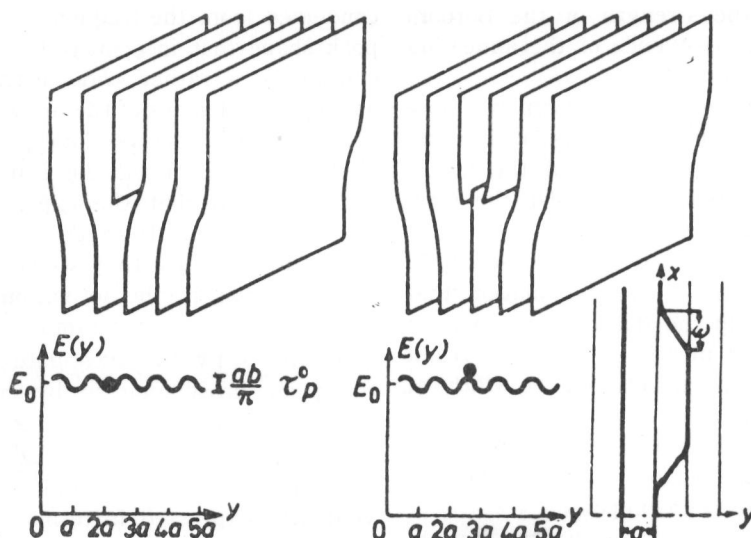


Fig. 1. The Peierls stress and the mechanism for the Bordoni relaxation.

$E(y) = E_0 + \frac{ab}{\pi} \sin \frac{2\pi}{a} y$ = line energy of a straight dislocation line as a function of position y .

(a = lattice parameter in y -direction).

E_0 = mean line energy

$\frac{ab}{\pi} \tau_p^0 \sin \frac{2\pi}{a} y$ = the Peierls energy (per unit dislocation length)

τ_p^0 = the Peierls stress.

The diagram in the lower right hand corner shows two kinks (of width w) in an otherwise straight dislocation line running along the x -direction.

investigated, relaxation peaks have been found which have been attributed to the same mechanism as the original "Bordoni peaks". The materials investigated in most details are the f.c.c. metals. To a first approximation the experiments on these metals have confirmed the essential predictions of the theory, in particular the intrinsic nature of the relaxation process.

Possibly the best founded prediction of the theory is that the relaxation process should be present immediately after low-temperature deformation, without any warming up of the deformed sample beyond the temperature of the peak. This prediction has been verified on Cu or Au after the deformation at liquid helium temperature by Bruner and Mecs^(11, 12) and Okuda⁽¹³⁾. If migration of point defects to dislocations were an essential prerequisite for the relaxation process, it would only appear after the annealing at temperatures high enough to allow the migration of the point defects. A somewhat surprising feature of these low temperature experiments was that the N-W peak has about the same relaxation strength as the proper Bordoni peak

on the first warming up. It is only after warming up above the peak temperature that the strength of the N-W peak is reduced to be smaller than that of the Bordoni peak which is familiar from the experiments after room temperature deformation.

Several conclusion may be drawn from the annealing behaviour observed after the low temperature deformation: (1) The N-W peak is due to a relaxation process in its own right. (2) It involves presumably the same basic dislocation process as the Bordoni peak (the main peak after room temperature deformation). The dislocations involved, however, are of a different character. (3) The dislocations responsible for the N-W peak are more easily pinned by point defects than those responsible for the Bordoni peak, since in the temperature range in which we expect the migration of point defects to dislocations the N-W relaxation strength is considerably more reduced than the relaxation strength of the Bordoni peak. (4) In certain temperature ranges below room temperature, unpinning by either the evaporation of point defects or the annihilation at dislocation lines may be important, as indicated

by increases in the strength of the Bordoni maximum as a consequence of the annealing in these temperature ranges.

If theory and experiment are compared more closely, a number of deviations of the experiments from the predictions of the simple theory become apparent. We list the most important ones of these points.

(1) In Pt, only one peak is observed¹³⁾. This may have the trivial explanation that the N-W peak and the Bordoni peak happen to coincide in this metal, *e.g.* as the result of a particular relation between the widths of two types of extended dislocations involved. No detailed experimental study to check this possibility has been performed, nor alternative explanations have been proposed.

(2) In the majority of the crystals investigated, the width of the Bordoni peak (as well as that of the N-W peak) is considerably greater (by a factor two to three) than one would calculate from the measured activation energy for a single relaxation process. If this were a general result, it should be accounted for by the theory in a straightforward way. However, it appears that for aluminium single crystals (H. Sack: private communication), peaks almost as narrow as predicted by the single relaxation time theory are observed.

(3) The position of the relaxation peaks is not completely independent of such factors as the degree of cold-work, impurity content, the annealing and the neutron irradiation. The behaviour in this respect seems to vary from one group of materials to another. For example, the annealing behaviours is different for f.c.c. and for b.c.c. metals.

At the present time it appears that the interpretation of the extra width of the Bordoni peaks is the key problem in the explanation of the deviations between the experiment and the simple theory. The importance of this question had very early been stressed by H. Sack (private discussions). The variation of the peak position with impurity content, annealing history etc. may be largely due to changes of the relative contributions of the various processes contributing to the extra peak width. At least in a formal way the question may be asked whether the extra width is caused by a distribution in the frequency factor, or in the activation energies of the relaxation time spectrum, or in both. Bordoni *et al.*¹⁴⁾

concluded from the frequency variation of the peak shape that in copper the extra width is caused by a rather wide distribution in the attempt frequencies of the individual processes contributing to the Bordoni peak in copper. Niblett¹⁵⁾ re-examined the experimental data and concluded that the experiments do not allow a decision. If anything, among the two simple possibilities, they would rather favour a distribution in the activation energies and not in the frequency factors.

Another way to investigate the nature of the peak broadening is by comparing the internal friction at the peak maximum $Q_{\max}^{-1} \equiv \delta_{\max}/\pi$ with the effect of the relaxation process on the elastic modulus, which is conveniently expressed in terms of the relative change of the frequency of the vibrating specimen $\Delta f/f$. For single relaxation peaks these two quantities are equal, *i.e.*

$$Q_{\max}^{-1} = \frac{\delta_{\max}}{\pi} = \frac{\Delta f}{f}. \quad (1)$$

Experimentally, for both the N-W peak and Bordoni peak

$$\frac{\Delta f}{f} / Q_{\max}^{-1} > 2. \quad (2)$$

is observed. This means that more than two relaxation processes contribute to each peak. If we assume that the width of the peaks is due to the superposition of single relaxation processes associated with different dislocation types¹⁶⁾, at least $2 \times 3 = 6$ different dislocation types are required. It appears to us that it is unlikely that so many different dislocation types, grouped in two sets of similar relaxation times, are associated with the relaxation process. We are rather inclined to think that only two different dislocation types are involved (*e.g.* 0° - and 60° -dislocations), the broadening of the peaks being due to other causes.

Instead of $Q_{\max}^{-1}$, the total area A under the relaxation peak may be used for the comparison with Δf . If we deal with a single relaxation time

$$\tau = \tau_0 \exp(U/kT). \quad (3)$$

(U denotes the activation energy of the process, kT has the usual meaning), the relation

$$A = \pi^2 \cdot \frac{k}{U} \cdot \frac{\Delta f}{f}, \quad (4)$$

can easily be shown to hold. For a superposition of relaxation processes with activation

energies U_i and frequency defects Δf_i , the area under the peak is given by

$$A = \pi^2 \frac{k}{f} \sum_i \frac{\Delta f_i}{U_i}. \quad (5)$$

If all U_i are equal, and therefore the distribution is entirely one in the τ_0 's, the summation in eq. (5) may be carried out and gives eq. (4). For copper and gold^{(13), (14), (16)} the measured area A is by about a factor of two larger than the value calculated by means of eq. (4) from the measured values of U and $\Delta f/f$. This shows that in these metals a distribution of the activation energies must exist, which may or may not be accompanied by a distribution in the frequency factors. In the way of contrast, eq. (4) is fulfilled for the b.c.c. metal Ta⁽¹⁷⁾, indicating that there is an appreciable spread in the relaxation times τ_0 but not in the activation energies. This result together with the above-mentioned observation on the peak width in aluminium suggests that the nature of the extra width of the peak is a secondary feature of the relaxation process and may vary from crystal structure to crystal structure and from material to material. It supports the view that the shifts in peak position and peak shape caused by impurities, annealing etc. is also connected with secondary processes.

The extension of the theory to account quantitatively for these "secondary" features has proved to be rather difficult. As discussed elsewhere⁽¹⁸⁾, a number of attempts to ascribe the extra width to a basic feature of the kink formation process have been unsuccessful. This is in agreement with the deduction from the experiments made above.

At present the best approach to all the open problems mentioned here appears to be the simultaneous consideration of kink formation and kink propagation. It appears that the finite velocity of kink migration⁽¹⁹⁾ contributes to the broadening of the Bordoni peak. The kink propagation will be influenced by impurities, point defects, jogs and internal stresses. The details of the interaction of kinks with impurities and point defects may depend on the nature of the crystal under consideration and may have to do with the rather large differences observed between different crystal classes. Such an approach promises to give a unified viewpoint not only for the Bordoni relaxation, but also for the

low amplitude background internal friction due to dislocations and the Hasiguti peaks which, according to Hasiguti⁽²⁰⁾, may be due to the interaction of kinks with point defects. An outline of such a unified approach has been given earlier⁽¹⁸⁾. The theory is at present in an active and promising state of development and will be reported in a contribution to Vol. III of Physical Acoustics, edited by W. P. Mason.

In summary, it may be said that to a first approximation the experiments of the last few years have confirmed the kink formation theory of the Bordoni relaxation. To a second approximation, there are a large number of differences between experiment and theory, the details of which, however, vary from crystal class to crystal class. It appears that these deviations are not due to serious inadequacies of our ideas on thermally activated formation of kink pairs. Rather, they seem to be associated with the propagation of the kinks and with their interaction with impurities, point defects, jogs, and internal stresses (other dislocations). A unified treatment of both the formation and the propagation of kinks is being carried out and promises to give a satisfactory treatment of a large class of internal friction phenomena, including some of the finer details of the Bordoni relaxation.

Acknowledgements

The authors would like to express their appreciation to H. Sack and S. Okuda for interesting discussions and the communication of unpublished results.

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JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 18, SUPPLEMENT I, 1963

A Note on the Peierls Force

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A simple theory of the Peierls force in covalent crystals was developed. The calculated Peierls forces were 460 kg/mm² in silicon and 253 kg/mm² in germanium. If there were an internal friction peak due to Seeger's mechanism in germanium, it might be observed at 1300°K for 40 kc/s. The internal friction peak observed at 380°C for 40 kc/s by Kessler was suggested to be due to the motion of kinks dragging vacancies. The low temperature internal friction peaks in some crystals with high Peierls force may be due to the same origin.

1. Introduction

Since Seeger¹⁾ and his co-workers²⁾ have developed the theory of the Bordoni peak relating to the Peierls force, many works on this phenomenon appeared to obtain informations about the Peierls force. Peierls forces derived from the measurements of the Bordoni peaks in Al₂O₃³⁾, MgO^{3), 5)} and LiF^{4), 6), 7)} are almost equal to that of copper or less than it. This situation is very difficult to understand from the known mechanical properties of these crystals, and it may raise a doubt about the Seeger theory of the Bordoni peak.

The most valuable test of the Seeger theory of the Bordoni peak may be the exact calculation of the Peierls force and comparison with the low temperature internal friction. Now it might be possible to calculate the Peierls force at a reasonable degree of approximation by the help of high speed computing machine in typical metals such as copper, and in typical ionic crystals such as NaCl, KCl. The calculation of the Peierls force, however,

seems to be carried out more easily in covalent crystals because of its high value, and very recently the present author discussed fully the Peierls force in covalent crystals.

In this note a brief account of the calculation of the Peierls force was given and the relation between the Peierls force and the internal friction in germanium measured by Kessler⁸⁾ was discussed.

2. The Peierls Force in Covalent Crystals

The perturbation in the atomic configuration around a dislocation is too large to apply any standard approximation to the evaluation of the electronic structure. We are, however, concerned only with the cohesive energy, so the simplest tight binding approximation used by Leman and Friedel⁹⁾ may provide a plausible method to treat the energy change during the motion of a dislocation in the covalent crystal.

In Leman and Friedel's approximation the energies of the valence electrons are shown