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Dislocation damping in metals

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Abstract. Dislocations in metals give rise to damping or internal friction in a variety of ways. It is now possible to recognize experimentally at least five quite distinct types of damping. The present experimental position is briefly reviewed and short discussions are given of the underlying mechanisms responsible for the friction. Indications are given of points requiring further study.

1. Introduction

The mechanical energy of a vibrating solid is rapidly dissipated into heat, even if the body is completely isolated from its surroundings. The property of the solid responsible for the conversion of energy is called its *damping* or *internal friction.* We usually measure internal friction by observing either the decay of free oscillations, the resonant Q value of the system, or the absorption of high frequency sound. The Q value is generally a large number, and to a good approximation

$$\frac{\delta}{\pi}=\frac{1}{Q}=\frac{\alpha\lambda}{\pi}$$

where δ (or Δ) is the logarithmic decrement of free oscillations and α the coefficient of absorption of a sound wave of wavelengh λ.

A wide variety of mechanisms give rise to internal friction, and some of the most interesting concern the motion of dislocations in metals. The friction associated with this motion takes several forms, and involves parameters such as the density and distribution of the dislocations which are not too well known. However, it is now possible to identify at least five quite distinct processes each responsible for a characteristic type of damping. We first enumerate these briefly, and then go on to discuss each in turn.

2. Five types of damping

Dislocations in a vibrating metal may behave in a way which we describe by the so-called string model. That is, we consider lengths of dislocation anchored between two fixed pinning points which may be either impurity atoms or intersections with other dislocations. We picture these lengths vibrating as stretched strings subject to a viscous damping. In this case there will be damping which is independent of the strain amplitude of the oscillations.

Another type of internal friction arises from the hysteretic motion of dislocations (Granato and Lücke 1956). Suppose that a length of dislocation line is securely anchored at each end, either to other dislocations or to point defects, and that it is pinned less firmly at intermediate points to other point defects which have a mean separation L_c. On applying a stress to the specimen, the dislocation will bow out as in (*b*) and (*c*) of figure 1; this motion will be reversible save for any viscous damping of the moving dislocation which we here ignore. However, as the stress is increased, it eventually becomes great enough to pull the dislocation away from one of the point defects, this will occur at one end of the longest segment of dislocation line. As the length of the longest segment is thus increased, the stress can now immediately unpin the dislocation from all the other points (figure 1(*d*)). Subsequently, the line takes up the positions shown in (*e*), (*f*) and (*g*) of figure 1, finally becoming re-pinned as the stress falls to zero. We see that the motion of the dislocation is different on the outward and return paths. Therefore it we apply an oscillatory stress to such a system, the stress–strain curve includes a hysteresis loop, and this results in the presence of damping.

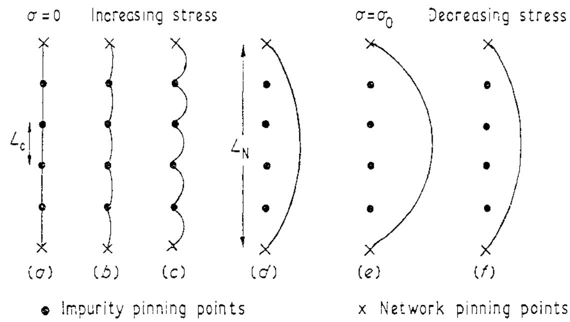

Figure 1. Schematic representation of the bowing out and unpinning of dislocation loops by an increasing and decreasing applied stress (after Granato and Lücke 1956).

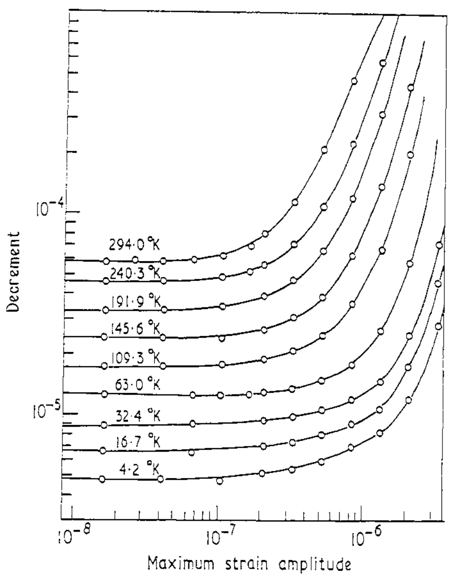

Figure 2. The internal friction of a copper single crystal as a function of strain amplitude and temperature, measured at 40 kc/s (Caswell 1958).

Figure 2 shows measurements on an annealed copper single crystal at various temperatures (Caswell 1958). At low strain amplitudes the decrement is independent of strain amplitude, but at higher amplitudes rises rapidly. This latter component we associate with the Granato and Lücke mechanism. It has become common to resolve the total decrement Δ into two components:

$$\Delta = \Delta_{\mathrm{I}} + \Delta_{\mathrm{H}}$$

where Δ_{I} is the decrement observed at the lowest amplitudes and Δ_{H} the amplitude dependent component. However, we must remember that the two mechanisms giving rise to

Δ_I and Δ_H may not be entirely independent of each other, and therefore the resolution may not be too precise.

Another process occurs at relatively high temperatures, that is well above room temperature. It seems that the motion of a dislocation through a lattice may create new defects in the lattice, probably vacancies. The energy of formation of these defects comes from the kinetic energy of the moving dislocation, which is therefore damped. Fourthly, we have the so-called Bordoni peak (Bordoni 1947). In a wide range of metals, cold working

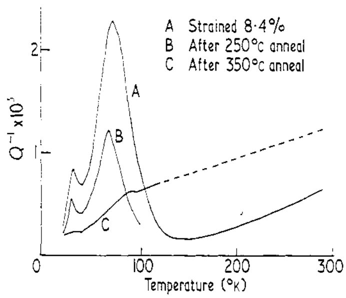

Figure 3. The internal friction of cold-worked polycrystalline copper measured at 1100 c/s (Niblett and Wilks 1957).

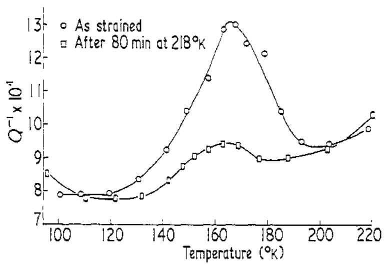

Figure 4. The internal friction of polycrystalline copper strained 4·5% at 90°K, measured at 1 c/s (Baxter and Wilks 1962a).

produces a characteristic peak in the plot of internal friction against temperature in the region of 100°K (see for example Sack 1962). A typical peak (in copper) is shown in figure 3. Lastly, there is a group of perhaps three peaks, which in copper have been observed at about 200°K. These have been labelled P_1, P_2 and P_3 by Okuda and Hasiguti (1963). The position here is somewhat confused, and for the most part we will concentrate on one of the peaks, the so-called P_1. A typical example of this peak, again in copper, is shown in figure 4.

As we discuss these five processes in detail, we shall see that an increasing degree of sophistication is necessary to account for the various results. The string model is essentially quite simple, and pictures the dislocation as a vibrating elastic string which is securely fastened to pinning points at each end. To account for the hysteretic damping we introduce the possibility that the dislocation may break away from a pinning point. Yet the pinning process is still somewhat idealized: a dislocation is either pinned to a point defect or is quite free. We assume that we are dealing with an on–off process. In addition the theory also ignores the effects of thermal fluctuations, the model is essentially at absolute zero.

The damping at high temperatures reminds us that the moving dislocation is not an elastic string. It is a complex lattice defect which can be responsible for the formation of new defects in the crystal. To explain the Bordoni peak we have to modify our string model still further. In particular we must appreciate that the dislocation is very flexible. Hence if it is held up at some potential barrier it will prefer to move forward by throwing out a small bulge rather than moving forward as a rigid rod. When we come to consider the peaks P_1, P_2, P_3 we find ourselves involved in the details of how a dislocation interacts with a pinning point. Having come so far, we may then perhaps be in a position to return to the Granato and Lücke model and consider again what is the effect of temperature on the pinning of dislocations by point defects.

3. The vibrating string model

According to this model the equation of motion of a dislocation line may be written

$$A\frac{\partial^2 y}{\partial t^2} + B\frac{\partial y}{\partial t} - C\frac{\partial^2 y}{\partial x^2} = b\sigma_0 \sin \omega t \tag{1}$$

where y is the lateral displacement at a position x along the length, A an inertial term, B the damping force per unit length, C the line tension associated with the dislocation, b the strength of the dislocation and $\sigma_0 \sin \omega t$ the resolved component of the applied stress in the slip plane of the dislocation. By solving equation (1) Granato and Lücke (1956) obtained expressions for both the logarithmic decrement Δ_I and for the modulus defect ΔE. (The modulus defect is the apparent reduction in the elastic modulus due to the non-elastic strain which results from any motion of the dislocations.) For not too high frequencies, it is found that

$$\Delta_I = \frac{\Omega \Lambda L^4 B \omega t_1}{\pi^3 C} \tag{2}$$

$$\left(\frac{\Delta E}{E}\right)_I = \frac{\Omega \Lambda L^2 t_2}{\pi^2} \tag{3}$$

where Ω is an orientation factor, Λ the dislocation density, L the mean length of a vibrating loop and ω the frequency. t_1 and t_2 are constants which take account of the fact that there is a distribution of loop lengths and that the longer lengths contribute disproportionately to the friction. We see from equations (2) and (3) that the decrement should vary as the

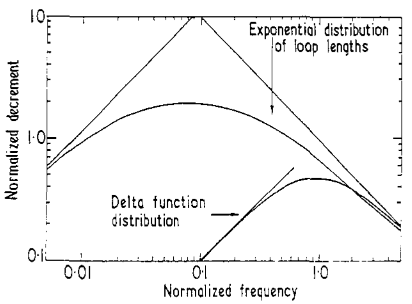

Figure 5. The maximum in the decrement as calculated for the vibrating string model by Stern and Granato (1962). The low and high frequency asymptotes for both curves have slopes of ± 1 respectively.

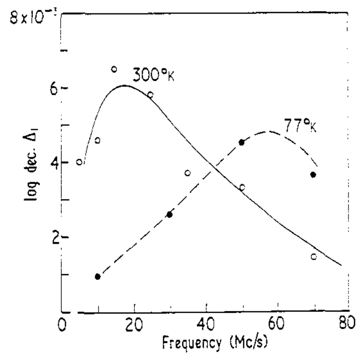

Figure 6. The attenuation of ultrasonic waves in an annealed copper crystal at two temperatures (Alers and Thompson 1961).

fourth power of the mean loop length, and the modulus defect as the square of that length. Evidence of these characteristic relations has been obtained by Thompson and Holmes (1956) who observed the friction of copper single crystals subject to neutron irradiation. The irradiation introduced additional point defects on the dislocations, which reduced the length of the vibrating loops. The authors showed that the rate of decrease of the decrement and modulus was consistent with the L^4 and L^2 dependence in the above equations.

The most convincing evidence for the vibrating string model arises from the fact that the general solution of the equation of motion of the string model predicts the presence of a damped resonance at a frequency of the order of tens of megacycles. The form of this solution in normalized units is shown in figure 5 (Stern and Granato 1962). The figure gives calculated values of the damping both for an exponential distribution of loop lengths and for loops all of the same length. Although a resonance is observed in both cases there is a considerable difference in its position and form. This resonance has been observed by Alers and Thompson (1961) and by Stern and Granato (1962). The former authors measured the internal friction of a copper single crystal before and after a large dose of neutron irradiation, and observed a considerable reduction Δ_L in the internal friction after the irradiation. They then assumed that the reduction came about because of the complete pinning down of the vibrating string component. In this case the contribution Δ_I to the friction in the original specimen is equal to the observed change Δ_L. Figure 6 shows the value of Δ_L plotted as a function of frequency for two different temperatures; a resonance is clearly visible in each case.

In a rather similar experiment, Stern and Granato (1962) observed the strain independent friction Δ_I as a function of neutron irradiation. The value of Δ_I at all frequencies (5 to 45 Mc/s) decreased steadily with increasing irradiation on account of the pinning of the dislocations. In addition, however, the position of the resonance moved to considerably higher frequencies in accord with the predictions of the string model for shorter loop lengths.

A very characteristic feature of the results in figure 6 is that the peak moves to a higher frequency at a lower temperature. This is just the reverse behaviour to what is observed in many so-called relaxation processes governed by activation energies (which we consider in connection with the Bordoni peak). As discussed by Stern and Granato (1962) the position of the resonance shifts with temperature because the viscous damping term B is a function of temperature. According to Leibfried (1950) this damping arises from the interactions of the dislocation with the thermal vibrations of the crystal. The energy of the dislocation is dissipated as phonons and it turns out that, in the temperature regions of interest, the damping should be proportional to the absolute temperature. That is, the constant B in equation (1) increases with rising temperature, with the result that the resonance is shifted to a higher frequency.

As in most experiments on internal friction several variables are involved, and it is not possible to make precise estimates of absolute magnitudes. Nevertheless, by taking plausible values for the various parameters, Stern and Granato are able to give a reasonable account of the friction in the region of the resonance. We note, however, that the measured resonances are sometimes appreciably broader than those predicted theoretically. Stern and Granato point out that these results could be described in terms of the motion of two sets of dislocations (perhaps of edge and screw orientation) with somewhat different characteristic parameters. (A rather similar suggestion has also been made by Thompson and Paré (1960) in connection with other experiments on the internal friction of irradiated copper.)

There still remains the question of the dependence of the friction on frequency at lower frequencies. The model predicts, without ambiguity, that in this region the friction should be proportional to the frequency. Such behaviour has been observed by Hiki (1958) in measurements on lead at 64 and 192 kc/s. However, there is a big question mark over this part of the subject because there are several measurements which seem to imply that the strain amplitude independent friction does not vary very much with frequency at lower frequencies. That is, the values of the low frequency friction are of about the same order as that observed at higher frequencies (see, for example, Takahashi 1956 and Weinig and Machlin 1956), whereas extrapolating downwards from the high frequency values we would expect them to be much smaller.

Some authors have tried to explain the above discrepancy by pointing out that in the region of the resonance the decrement remains fairly constant over a wide range of frequency. This effect is shown for example in figure 7 which gives an extrapolation of experimental results to much lower frequencies (Stern and Granato 1962). However, below 10 kc/s the dependence of the decrement on frequency is approaching a linear relation. It is, unfortunately, difficult to make measurements over a wide range of frequency on a single specimen for reasons of experimental technique. It is also hazardous to make comparisons between measurements on different specimens. However, if we force ourselves to draw some conclusion from all the measurements at lower frequencies, then the friction appears to be approximately independent of frequency rather than proportional to it.

To sum up, we can say that the string model gives a good account of the strain independent friction at megacycle frequencies but not at lower frequencies. The reason for this discrepancy is still not clear. The natural explanation is that there is some other process present in the crystals which gives rise to a damping at low frequencies which is approximately independent of frequency. However, there is little information at present as to what this may be. Experimentally, it is important to note that the friction given by the vibrating string model becomes extremely small at low frequencies. Therefore any experiment to observe it must be carefully arranged to avoid friction of comparable or greater magnitude arising via other mechanisms.

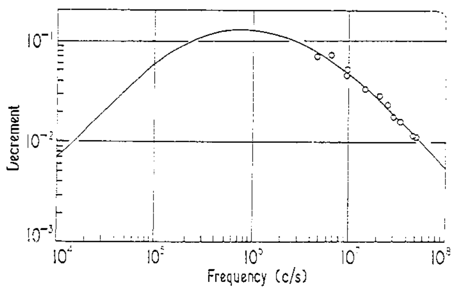

Figure 7. Measurements of the damping in copper at 195°K (Alers and Thompson 1961) are fitted to a theoretical curve so as to give the smallest possible extrapolated decrement at 10 kc/s (Stern and Granato 1962).

4. The unpinning model

On the hysteretic pinning model the internal friction is given by the relation

$$\Delta_{\mathrm{H}} = \frac{\Delta W}{2W} = \frac{\Delta W}{\sigma_0^2/G} \tag{4}$$

where ΔW is the area of the hysteresis loop, W the total energy of the vibration, σ_0 the maximum amplitude of the oscillating stress and G the shear modulus. In order to arrive at the internal friction of a real crystal, Granato and Lücke (1956) make two simplifying approximations. Firstly, the distance L_{n} between network nodes is assumed to be constant within a given specimen. Secondly, the distribution of the impurities along the dislocations is assumed to follow an exponential law, so that the number of dislocation segments with length between l and $l + dl$ is given by

$$N(l)\,dl = \frac{\Lambda}{L^2} \exp\left(-\frac{l}{L}\right) dl$$

where Λ is the dislocation density and L the mean length of a segment.

On the above assumptions Granato and Lücke (1956) calculate the internal friction to be

$$\Delta_{\mathrm{H}} = \frac{\Omega \Lambda L_{\mathrm{N}}^3}{\pi^2 L_{\mathrm{c}}} \frac{K\eta a}{L_{\mathrm{c}}\epsilon_0} \exp\left(-\frac{K\eta a}{L_{\mathrm{c}}\epsilon_0}\right) \tag{5}$$

where Ω is an orientation factor which takes into account the fact that the resolved sheer stress on the slip planes is less than the applied stress, K is a factor (also dependent on orientation) connected with the stress required to produce unpinning, η is Cottrell's misfit parameter, a the atomic spacing, L_{c} the mean distance between the impurity atoms pinning the dislocations, ϵ_0 the maximum value of the oscillating strain. We may write equation (5) in the form

$$\log \Delta_{\mathrm{H}}\epsilon_0 = A - B/\epsilon_0 \tag{6}$$

where A and B are two constants. In addition, the modulus defect is given by

$$r(\Delta E/E)_{\mathrm{H}} = \Delta_{\mathrm{H}} \tag{7}$$

where r is a constant of order unity. (If the strain amplitude ϵ_0 varies over the dimensions of a specimen, a slight modification of equation (6) is called for (see Granato and Lücke 1956). Although this point is often overlooked, it fortunately does not make much difference in practice.)

Figure 8 shows measurements by Chambers and Smoluchowski (1960) on a single crystal of aluminium. As in dealing with figure 2, we may analyse the friction into two components, one varying with strain amplitude and the other independent of it. Figure 9 shows the strain amplitude dependent component Δ_H plotted in the manner suggested by equation (6). We see that the points fall on quite good straight lines as suggested by the theory; the slopes of the lines decreasing with rising temperature. The authors explain this change in slope by remarking that, as the temperature rises, the impurity atoms pinning the dislocations will tend to diffuse away. That is, the mean distance L_c between pinning points

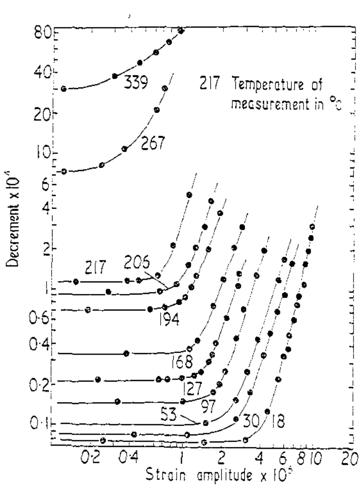

Figure 8. The internal friction of an aluminium single crystal measured at different temperatures and at ~15 kc/s (Chambers and Smoluchowski 1960).

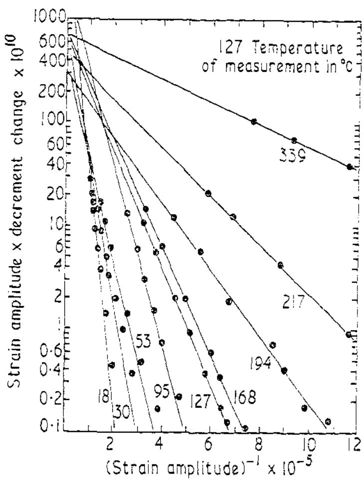

Figure 9. Granato and Lücke plots of the internal friction of the aluminium single crystal shown in figure 8 (Chambers and Smoluchowski 1960).

tends to become longer. The effect of this increase in L_c will be most apparent via the exponential term in equation (6), and hence the friction should increase with increasing temperature. In addition Chambers and Smoluchowski show that the measured values of the modulus defect may be written in the form of equation (6).

In the above experiments the friction increases with rising strain amplitudes, but the Granato and Lücke model implies that at sufficiently high strain amplitudes the friction will begin to fall. The friction increases initially because a greater strain produces more unpinning. Eventually, however, the strain becomes so large that the dislocation is unpinned from all the pinning points every cycle. In this case the area of the hysteresis loop becomes independent of strain amplitude whereas the mechanical energy of the oscillating system continues to increase. Hence, according to the relation $\Delta_H = \Delta W/2W$ (equation 4), the internal friction begins to fall. Figure 10 illustrates such behaviour in lead (Hiki 1958). At low temperatures the friction rises with strain amplitude, but at the higher temperatures the reverse effect is observed. As in the experiments on aluminium, it appears that the effect of rising temperature is to disperse the impurities pinning the dislocations; the distance between pinning points increases, and unpinning occurs more readily. Hence complete unpinning occurs at a lower strain amplitude at higher temperatures. The same author has verified also that the friction appears to be independent of frequency, as is predicted by equation (5). References to other measurements of the internal friction in accord with the unpinning model (including the effect of impurity concentration) are given by Granato and Lücke (1956) and Niblett and Wilks (1960).

Although there is a well defined group of experiments which demonstrate the unpinning type of internal friction, several details of the underlying process are still not clear. It sometimes turns out that the plots of ln $\Delta_H \epsilon_0$ against ϵ_0^{-1} are not straight but somewhat curved. That is, the measured friction at low strain amplitudes appears to be greater than that predicted by the theory. Several authors have attempted to account for this effect. Some have argued that the model is essentially correct but that the calculations are not yet sufficiently refined. As mentioned above, the model only applies to temperature zero, and Teutonico, Granato and Lücke (1964) have recently extended their treatment to take account of thermal fluctuations. Unfortunately the results turn out to be very complicated. Rogers (1962) has pointed out that when the dislocations unpin there will

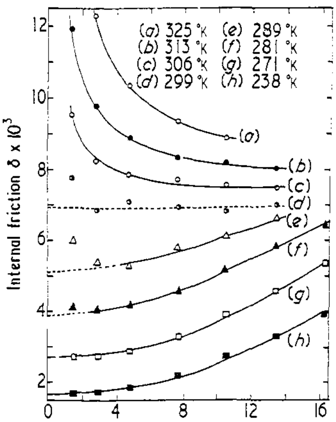

Figure 10. *The internal friction of a lead single crystal at various temperatures as a function of strain amplitude, measured at 64 kc/s (Hiki 1958).*

be an increased contribution from the vibrating string type of friction because of the longer loop lengths. Other authors have suggested that the model itself is not correct. For example Gelli (1962) has remarked that the theory pictures the impurities situated actually on the dislocation, whereas it would be more realistic to picture them as an atmosphere extending over some small region. In this case, there is the possibility of a hysteretic motion within the atmosphere at low strain amplitudes, and another hysteretic motion at higher amplitudes as the line breaks away from the atmosphere altogether. Unfortunately all these detailed discussions are at present somewhat inconclusive because of the difficulty of specifying all the various parameters which are important. In particular we must remember that the dependence of the friction on strain amplitude (equation (6)) is largely determined by the distribution function for the lengths of the dislocation loops L_N. Granato and Lücke assume the exponential function mentioned above, but there is little confirmation of how good this approximation is for any given specimen. (We touch on this point again in §8.)

Finally, we mention some quite different measurements by Roberts and Brown (1962). These are essentially static measurements of the internal friction of zinc single crystals. The authors applied a given stress to a crystal and observed the strain by observing the change in length of the specimen with a high sensitivity capacitance technique. In this way they were able to trace out the actual hysteresis loops; some typical results being shown in figure 11. Bearing in mind that the internal friction is proportional to the area of the loop ΔW, we see that equation (6) implies that ln $(\Delta W)\epsilon_0$ should be proportional to ϵ_0^{-1}.

Figure 12 shows some of Roberts and Brown's results plotted in what is essentially this form, although they replace the strain by the stress. We see that the plots give good straight lines as in the other Granato and Lücke plots in figure 9.

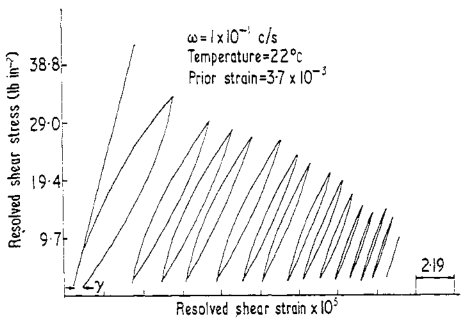

Figure 11. Hysteresis loops observed in single crystals of zinc (Roberts and Brown 1962)

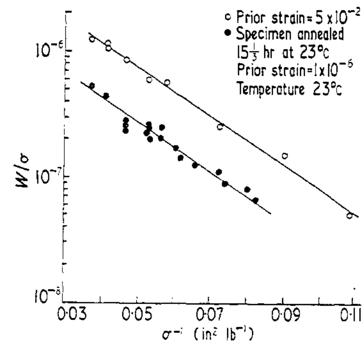

Figure 12. Granato and Lücke type plots for hysteresis loops in zinc (Roberts and Brown 1962).

At first sight, the above measurements appear to give good support to the Granato and Lücke theory. However, it seems that they also present some new problems. Thus the essence of the Granato and Lücke mechanism is the asymmetry of the stress–strain curve, which results in a hysteresis. Yet the loops observed by Roberts and Brown appear to be quite symmetrical. The position here is still obscure and more experiments are required by this new and promising technique. (It will also be of interest to observe a complete cycle including compression of the specimen as well as tension.)

5. Friction at high temperatures

We now briefly refer to a quite different type of friction. That is to the amplitude independent friction observed at low strain amplitudes at high temperatures. Figure 13 shows the results obtained on an aluminium single crystal by Chambers (1957). Above about 200°c the friction rises exponentially as the reciprocal of the absolute temperature. This

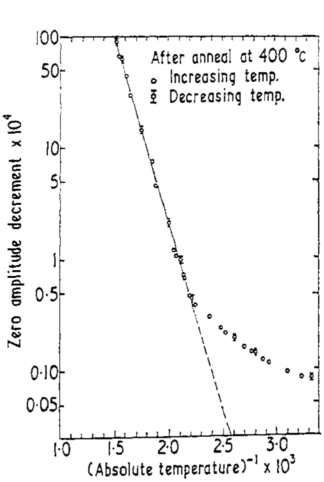

Figure 13. Amplitude independent friction of an aluminium single crystal as a function of temperature (Chambers 1957).

increase is probably associated with the formation of defects by the moving dislocation; the exponential dependence of the friction on the reciprocal temperature then follows naturally (see for example Niblett and Wilks 1960.) This process appears to be quite distinct and separate from the other processes we are discussing, and will not concern us further. (This type of friction has been recently discussed by Schoeck, Bisogni and Shyne (1964).)

6. The Bordoni peak

Figure 3 shows the Bordoni peak in a specimen of cold-worked copper; it is generally accompanied by a subsidiary peak on the low temperature side. The position of the peak shifts to high temperatures with rising frequency, suggesting that an activation energy is involved. It seems probable that only the motion of dislocations is involved, and that interactions with point defects may be neglected. Thus a similar peak is observed in many cold-worked metals, irrespective of their degree of purity. Annealing the specimen causes the peak to disappear in a temperature range where we expect the dislocation density to be reduced. In addition, the annealing characteristics are quite different from those observed for the peaks P_1, P_2 and P_3, whose annealing behaviour clearly suggests that point defects as well as dislocations are present. Hence both the annealing behaviour, and the widespread occurrence, of the Bordoni peak suggest that we are dealing with a process in which only dislocations are involved. There are two principal treatments of how the friction may arise, due to Seeger (1956) and Brailsford (1961).

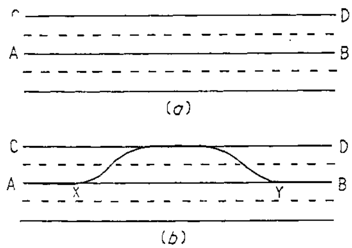

Figure 14. Seeger's mechanism: (*a*) dislocation in a position of minimum energy, (*b*) bulge in a dislocation. (Full straight lines represent positions of maximum energy.)

The essence of Seeger's treatment is illustrated in figure 14. AB is a length of dislocation line lying parallel to one of the close-packed directions in the crystal. It rests in equilibrium in a position of minimum potential energy in the so-called Peierls potential well. To reach the next equilibrium position CD it must pass through a potential barrier indicated by the dotted line. Suppose we now apply a stress to the system which tends to move the dislocation from the position AB to CD. Because a dislocation line is flexible it will not move to the new position CD as a rigid rod, because this would demand a large amount of energy. Instead it will prefer to make use of thermal fluctuations to throw out a small bulge as shown in figure 14(*b*). Once such a bulge has formed, quite a small stress is then sufficient to spread it out sideways thus carrying the whole dislocation to the position CD.

A bulge thrown out by a dislocation may be regarded as a pair of kinks of the kind which arise when a dislocation passes from one lattice line to the next. In the absence of any stress the two kinks will attract and annihilate each other, but an applied stress will tend to move them apart and increase the slipped area. For a given applied force there will be a certain critical separation of the kinks d_{crit} above which they will separate further and below which they will come together. Under the action of an oscillating stress the formation of these bulges leads to internal friction; the motion of the two constituent kinks is approximately reversible for small displacements, but as soon as the critical distance d_{crit} is exceeded they will move apart rapidly and irreversibly.

The length of a bulge formed by thermal activation will be determined by the criterion that its energy of formation is a minimum: a longer bulge would require more energy to surmount the Peierls barrier, while a shorter one would involve a disproportionate increase in the line energy. Thus this mechanism leads to a unique activation energy related to the critical size of the bulge. That is, Seeger's original treatment leads to an activation energy which is a constant for a given metal and is essentially independent of the presence of impurities and of the amount of cold work. In addition, the possibility of the activation energy being different for screw and 60° dislocations accounts naturally for the presence of the subsidiary peak on the low temperature side.

Seeger's first treatment has been developed by Seeger, Donth and Pfaff (1957), Donth (1957), Lothe (1960) and Seeger and Schiller (1962). These authors take into account the fact that, on a long length of dislocation line, many bulges will be formed on both sides of the line. It will therefore be possible for the kinks forming these bulges to diffuse into each other and, if they are of opposite sign, to annihilate each other. Quite involved discussions involving the theory of stochastic processes are necessary to allow for these effects. However, the general picture is not greatly changed as a result of these considerations, save that the activation energy should now depend weakly on the strain amplitude.

Although Seeger's mechanism gives quite a good account of the peak there are some difficulties. Paré (1961) has pointed out that when the bulge forms as in figure 14(*b*), the energy of the system is higher than when it is straight as in figure 14(*a*). Hence there will be a tendency for the bulge to jump back under the influence of thermal fluctuations to the position AB, that is a tendency for the bulge to disappear before there is time for its two constituent kinks to separate sideways. The measured activation energy for a given metal does not seem to have a unique value; attempts to derive the activation energy for copper from the frequency and temperature dependence of the peak lead to values of the energy ranging from 0·08 to 0·015 ev (see Niblett and Wilks 1960). The peak is broader than predicted, and there is no sign of as great a dependence of the friction of strain amplitude as derived by the more detailed theory of Seeger and Donth. However Paré (1961) has argued that the presence of internal stresses in the metal may go far to explain all these discrepancies.

To a first approximation the temperature at which the peak occurs is independent both of the amount of cold work and of the amount of impurity present in the metal. More detailed measurements show that with increasing cold work the temperature of the peak moves upwards by 2 or 3 degrees. Irradiation reduces the magnitude of the peak and appears to shift it down in temperature by 1 or 2 degrees. These temperature shifts are small, but have been observed by several authors (see Niblett and Wilks 1960). It is not yet clear how they can be explained by the Seeger–Donth treatment.

Finally, we note that the most important single parameter in Seeger's treatment is the magnitude of the energy barrier between the positions AB and CD of the dislocation in figure 14. This is the so-called Peierls barrier. In fact we may say that the Seeger theory enables us to deduce a value for this energy. This turns out to be in fair agreement with theoretical estimates, but unfortunately there are no other ways of arriving at the figure experimentally. The Peierls energy is related to the critical sheer stress of a metal, but the relation is by no means clear as we are again concerned with the precise way in which a dislocation overcomes potential barriers. More work, theoretical and experimental, is needed.

On Seeger's theory the Bordoni peak arises only from those dislocations lying parallel to close-packed directions in the crystal. Of course we must expect only a very small fraction of the total length of a dislocation line to take up such an orientation. A line will tend to take up a position in a trough of the Peierls potential, but the influence of this potential will be small compared with the other forces acting on the dislocation. Nevertheless, numerical estimates suggest that enough dislocations may be in the required position to give the Bordoni peak. The treatment of Brailsford also depends on the motion of kinks on a dislocation line, but uses a quite different approach.

Brailsford (1961) considers dislocations which are not parallel to close-packed directions in the lattice, but lie at a small angle to them. He pictures a dislocation line not as a straight string but as a series of steps divided from each other by kinks in which a step passes over from one lattice line to the next as shown schematically in figure 15. The motion of an oscillating dislocation is now regarded as a motion of the kinks towards one or other end of the line. Because the kinks take a certain time to diffuse along the line, we may define a relaxation time τ characteristic of the motion of a length of dislocation. As the motion of the kinks is essentially a random process,

$$\tau \propto l^2/D \tag{8}$$

where l is the length of a dislocation loop and D the diffusion constant for kink motion. If, as seems probable, the motion of the kinks is thermally activated, the diffusion constant D will be proportional to $\exp(E/kT)$ where E is some activation energy. Thus at low temperatures the relaxation time τ will be very long and at high temperatures very short; the intermediate conditions are just those required for the development of a relaxation peak.

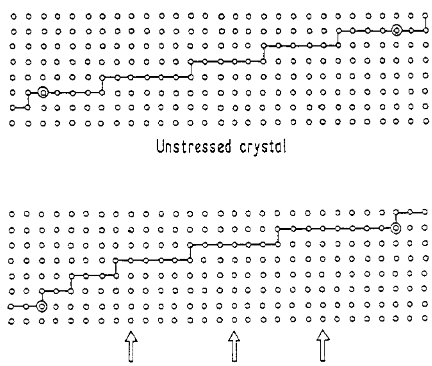

Figure 15. The motion of kinks along a dislocation line due to an applied stress (*after* Southgate and Attard 1963).

It is difficult to devise a clear-cut experimental test to distinguish between the theories of Seeger and Brailsford. In favour of Brailsford's treatment we note that it leads to a natural explanation of the shift of the temperature of the peak with cold work and irradiation. Thus the initial effect of cold work will be to increase the length of dislocation lines, and hence according to equation (8) to increase the relaxation time τ. Hence the peak shifts to a higher temperature. Similarly the effect of irradiation will be to reduce the length of dislocation loops and hence lower the temperature. Unfortunately, it does not seem possible to make quantitative predictions for given experimental arrangements.

Also relevant to Brailsford's treatment are some recent measurements of the amplitude independent friction and modulus defect in copper at temperatures down to 4°K (Bruner and Mecs 1963, Druyvesteyn and Blaisse 1962). In this temperature region both the damping and the modulus defect are considerably reduced by irradiation. Hence we conclude that in the unirradiated specimens there is a considerable motion of dislocations even at 4°K. At first sight this is not in accord with Brailsford's theory, which implies that at low temperatures dislocations become completely immobilized because the kinks can no longer diffuse along the lines. Certainly if the Bordoni peak in copper arises from the motion of dislocations according to Brailsford's mechanism, the same dislocations cannot be responsible for any friction at 4°K.

We have just referred to the difficulty of finding experiments which enable us to identify with certainty the mechanism responsible for the Bordoni peak. An allied problem is how to decide whether the rather similar peaks observed in metals other than copper arise from the same mechanism. For example, are the peaks observed in aluminium (Baxter and Wilks 1963) and various body-centred metals (Chambers and Schultz 1962) essentially Bordoni peaks, even though they behave differently in detail? What in fact are the essential experimental features of the Bordoni peak? Apart from its dependence on cold work, the most characteristic feature seems to be the shift in the temperature of the peak with cold working, neutron irradiation, and the addition of impurities. (Note that Chambers and Schultz (1962) have observed this effect in body-centred metals.) The annealing behaviour is also characteristic, in that the peak is only removed after a relatively high temperature anneal. In addition the annealing process shows a considerable amount of detail (see, for example, Niblett and Wilks 1960, Baxter and Wilks 1963, Okuda 1963), but at present appears too complex to give much clear information.

7. The peaks P_1 P_2 P_3

In copper there appear to be at least three peaks in the region of 200°K. To simplify matters we shall concentrate mainly on one of them, the so called P_1, shown in figure 4. There is evidence that this peak may be produced by cold work (see, for example, Niblett and Wilks 1957) and by neutron irradiation (Thompson and Holmes 1959).

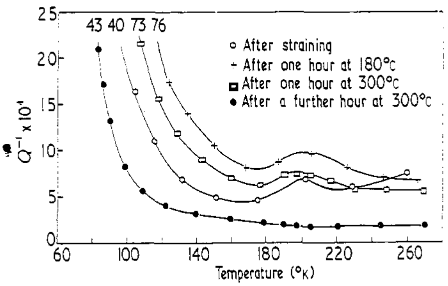

Figure 16. The internal friction of polycrystalline copper strained 5·4% (frequency 950 c/s). The figures on each curve indicate the maximum height of the Bordoni peak (Baxter and Wilks 1962a).

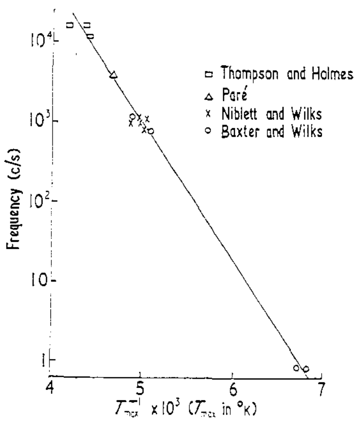

Figure 17. The frequency dependence of the temperature of the peak P_1 in copper (*after* Baxter and Wilks 1962a).

The annealing characteristics of P_1 are quite different from those of the Bordoni peak, as is shown by the results shown in figure 16. It anneals out well before the Bordoni peak, most of the annealing taking place at temperatures where one expects point defects to become mobile. P_1 also appears to be characterized by a well defined activation energy; thus figure 17 shows that a plot of frequency against reciprocal temperature leads to quite a good straight line over a wide range of frequencies. This again suggests that point defects are involved, for we expect the parameters of processes associated with point defects to be more closely defined than when dislocations are involved.

It appears, however, that point defects alone cannot be responsible for these peaks. From figure 17 we deduce an activation energy of 0·33 ev and an attempt frequency of 4×10^{11}. (The activation energy is the potential barrier which has to be overcome in the relaxation process, and the attempt frequency is the rate at which the system attempts to overcome this barrier.) For a point defect we would expect the attempt frequency to be of the order of the atomic frequency, that is about 10^{15} c/s. In fact the observed value of 4×10^{11} is more reminiscent of the frequency of vibration of lengths of dislocation line.

Another instructive experiment due to Koiwa and Hasiguti (1963) is illustrated in figure 18. The higher curve gives the friction of a specimen of copper which had been strained 9·8% in torsion and then allowed to rest for 17 days at room temperature. The specimen was then subjected to a further 0·35% torsion at 195°c; we see that this small additional deformation greatly reduced the size of the peak. Such behaviour has a natural explanation

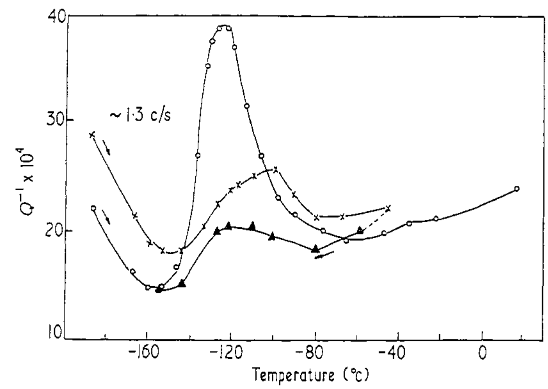

Figure 18. The internal friction of a polycrystalline copper wire deformed 9·8% by torsion: ○ after 17 days at room temperature; × after an additional 0·35% torsion at −195°c; ▲ after ∼ 10 min at −44°c (Koiwa and Hasiguti 1963).

if we assume that dislocations *and* point defects combine to give rise to the peak. The extra deformation pulls the dislocations away from the point defects, and the friction is lowered. Finally, we note that the rather variable behaviour of the peaks as reported by different authors is consistent with the variety of a system of dislocations.

It is not yet possible to give an exact description of mechanisms responsible for the peaks P_1, P_2, P_3. However, there seems little doubt that some form of interaction between a point defect and a dislocation line is involved. Okuda and Hasiguti (1963) have proposed a mechanism which is illustrated in figure 19. As discussed above, the vibration of a dislocation line may be described in terms of the motion of kinks. In the figure the motion

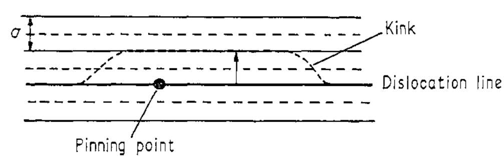

Figure 19. Schematic diagram of a dislocation line pinned down by a point defect (Okuda and Hasiguti 1963).

of a kink is impeded by a point defect located on a dislocation line, and we assume that the kink can only pass through the pinning point with the aid of thermal activation. In this case there is no impediment to the motion at high temperatures while at low temperatures no motion is possible at all. However, at some intermediate temperature the kinks will pass through the pinning point, but only after some hysteresis, and in the usual way we expect to observe a relaxation peak. Other rather similar mechanisms have been proposed by Kessler (1957), Bruner (1960) and Kamel (1961). Okuda and Hasiguti (1963) also suggest that we might identify the three peaks as being due to vacancies, interstitials and divacancies, but this is more tentative.

8. The nature of the pinning forces

As we have just seen, an understanding of the peaks P_1 P_2 P_3 involves a consideration of the nature of the interactions between dislocations and point defects. This brings us back to one of the questions which arose in connection with the Granato and Lücke hysteretic damping. In particular we are interested in how thermal activation affects the binding of a dislocation to a pinning point. To illustrate this point, we refer to an experiment by Baxter and Wilks (1962b).

In the course of some work on the internal friction of copper, we measured specimens in the form of rectangular bars about 8 cm long, 1 cm wide and about 2 mm thick. These were supported on the edges of two razor blades, and driven at their resonant frequency of about 1 kc/s by an alternating potential difference applied to an electrode placed below their centre. The motion of the bar was observed by an electrostatic pick-up at each end, and its internal friction derived by measuring the rate of free decay when the drive was cut off. Occasionally a rather curious behaviour was observed. As the amplitude of vibration was increased by increasing the driving force, a point was reached where the amplitude of vibration suddenly dropped by a factor of about 2. If the driving voltage was then held constant the vibrations slowly built up to their original large amplitude and then dropped again. This process would continue apparently indefinitely, the amplitude of vibration fluctuating with a period of the order of a fraction of a second.

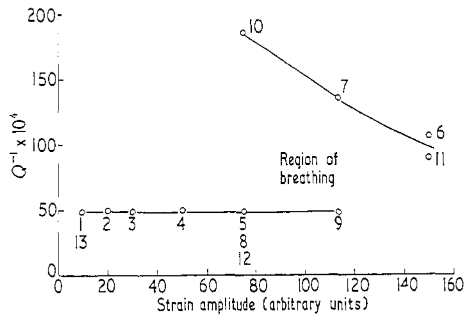

Figure 20. The internal friction at 90°K of a copper specimen which exhibited 'breathing'. The numbers indicate the order in which measurements were made (Baxter and Wilks 1962b).

Rather similar effects have been recorded by Takahashi (1952) and by Kessler (1957) although Kessler concluded that the effect was spurious and arose from some form of mounting losses. Baxter and Wilks (1962b) observed this effect in three or four specimens, and were able to make reproducible measurements on two of them. Figure 20 shows the internal friction of one of these specimens measured at 90°K; the figures on the diagram indicate the order in which the measurements were made, all by observing free decays. At low strain amplitudes the decrement was independent of strain amplitude. However, as the amplitude was increased the region of oscillation or 'breathing' was encountered, and the drive had to be turned up considerably to cause the specimen to vibrate steadily at a higher amplitude. Subsequent measurements of the friction in this high amplitude region were found to decrease with increasing strain as shown.

The form of friction shown in figure 20 accounts for the oscillatory 'breathing' behaviour. Suppose that the specimen is driven by a voltage just insufficient to produce breathing, and that this voltage is increased by a small amount. Initially the amplitude of oscillation will rise slightly, thus causing the friction to increase suddenly from the lower to the upper curve in figure 20. As the equilibrium amplitude of the oscillation at resonance is inversely proportional to the friction, the amplitude now falls towards lower values. However, before the strain amplitude reaches its new equilibrium, it will have dropped sufficiently for the friction to assume its lower stable value. When this occurs the amplitude of oscillation builds up, and the whole cycle is repeated indefinitely. The period of the motion is determined by the Q of the vibrating bar and the magnitude of the electrostatic drive.

The form of the friction shown in figure 20 can be interpreted as follows. In the strain independent region the dislocation remains firmly attached to all the pinning points, the damping perhaps arising through some string model process. As the strain amplitude is increased we usually expect unpinning to occur according to the Granato–Lücke model, that is a progressive breaking away of dislocation loops commencing with the longer lengths. However, it seems that in the present specimen the distribution of loop lengths happens, by chance, to approximate to a delta rather than an exponential function. Hence over a small range of strain amplitude the dislocations unpin from virtually all the pinning points, and there is an abrupt rise in the friction. The area of the hysteresis loop now has its maximum value and the friction falls off as the strain amplitude is further increased (cf. figure 10). (In confirmation of the above picture we note that after a specimen had been allowed to 'breathe' for a few minutes, the friction observed at the lowest strain amplitubes was considerably increased. Then, over a period of a few hours, this friction recovered to something like its original value. It appears that point defects diffuse away from the dislocation during the breathing process, and subsequently return. As the motion of the defects will essentially be a random walk, the period of return is much longer than the period of escape. Somewhat similar hysteresis effects have been reported by Chambers and Smoluchowski (1960).

Having gone so far, one interesting point remains. In order to account for the friction in figure 20 at high strain amplitudes, we postulate that it arises from a Granato and Lücke hysteretic mechanism. This type of damping only arises if a dislocation pins on to a pinning point *every* time it passes through its equilibrium position (see figure 1). If it sweeps through the pinning point without catching on, there is no hysteresis loop and no damping. We now remark that the results in figure 20 show another type of hysteresis effect, namely that the critical amplitude for the onset of breathing when approached from above is less than the critical amplitude when approached from below. This suggests that once dislocations become unpinned they are then reluctant to re-pin until the strain amplitude drops to a lower value. This is a situation quite different from that envisaged in the Granato and Lücke model. In that case the dislocation must re-pin on the reverse stroke after it has broken away. We are thus left to surmise that in these particular copper specimens there are two different types of pinning points. One type to which dislocations re-pin immediately, and another type to which they re-pin only when the amplitude has dropped. However, there is as yet no suggestion as to how these two types of pinning points may differ.

Finally, it is perhaps worth noting the frequency with which we encounter the suggestion that two types of dislocations are present in a specimen. For example, Stern and Granato (1962) make the suggestion in connection with the shape of the resonance curve associated with the string model. Thompson and Paré (1960) use the same suggestion to explain the effect of neutron irradiation and annealing on the internal friction of copper. If we accept Brailsford's theory of the Bordoni peak, then a second group of dislocations must be responsible for the modulus defect in copper in the region of 4°K. It remains to be seen whether these suggestions are merely a way of introducing more adjustable parameters into a complex problem, or represent a characteristic feature of the dislocation systems.

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