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ANOMALOUS INTERNAL FRICTION PEAKS AS FUNCTION OF STRAIN AMPLITUDE

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Abstract - Anelasticity, as suggested by Zener /1/ in 1948, gives rise to internal friction which is independent of the strain amplitude. The internal friction which increases with an increase of strain amplitude was explained by Koehler /2/ and Granato and Lücke /3/ in terms of vibration string and unpinning of dislocations. Early in 1949, Kê /4, 5/ observed in slightly cold-worked dilute aluminium-copper solid solutions a pronounced internal friction peak as a function of strain amplitude in which the high-amplitude side of the peak decreases rapidly to reach a very small value. The term "anomalous internal friction" was suggested by Kê /4/ in the sense that this anomalously amplitude-dependent internal friction is quite different from the amplitude independent internal friction formulated by Zener /1/ as well as from the "normal" amplitude dependent effect treated by Granato and Lücke /3/ in which the internal friction increases with an increase of strain amplitude and then decreases slowly and stays at an almost constant high value. This report reviews the experimental results concerning the anomalously amplitude-dependent internal friction peaks since the work of Kê in 1949, with emphasis on cold-worked f.c.c. metals (Al) containing Cu or Mg as substitutional solute atoms. In the light of the latest experimental results, a kink-dragging model is suggested.

I. Introduction

1. Early experiments - Anomalous low-frequency internal friction peaks were observed in 1949 in cold-worked high-purity aluminium containing 0.5 wt % of copper (partially annealed) in the temperature range of -5 to 125°C as is shown in Fig. 1. /4/ At temperatures within the region of the temperature internal-friction peak, amplitude internal-friction peaks were obtained when the internal friction was plotted as a function of strain amplitude (Fig. 2). /5/ It is seen that the amplitude curve shifts to higher strain amplitudes with an increase of temperature of measurement.

Further experiments showed that there is an aging effect associated with the anomalous behavior of the internal friction. /6/ The anomalous amplitude effect was found to reduce after each trial although the excitation strain amplitude was always kept the same in each trial. However, when measurements were taken after a period of time, the anomalous behavior was found to recover to its original extent and was once more reduced by successive trials. Experiments showed also that the previous application of a higher strain amplitude can shift the appearance of the anomalous internal friction to lower strain amplitudes.

In summation, the original experiments of Kê showed that: (1) The anomalous internal friction peak occurs in plastically-deformed specimens (Al), and disappears upon annealing at sufficiently high temperatures (recrystallization). This shows that this peak is related to the presence of dislocations, but it is different from the Hasiguti peak which disappears upon annealing at relatively lower temperatures. (2) This peak occurs only when some solute atoms (Cu) are present in the specimen (Al). Consequently, it is different from the Bordoni peak.
which is drastically reduced or suppressed by the presence of impurities. (3) The anomalous internal friction exhibits an aging effect. This indicates that the solute atoms interacting with the dislocations are mobile under the experimental conditions, so it cannot be explained by the original G-L model. (4) The amplitude internal friction peak shifts to higher strain amplitudes with an increase of temperature of measurement which is in contradiction with the prediction of the modified G-L model in which the thermal agitation is taken into account. (5) The effect of the previous application of a higher strain amplitude upon the anomalous behavior of the amplitude peak shows that the distribution of solute atoms around the dislocations is changed by the applied stress.

I. 2. Further experiments on the anomalous peak - The anomalous internal friction peaks were systematically studied in 1965 by K8 et al. in China, and low-frequency amplitude internal-friction peaks (as a function of strain amplitude) accompanying a strain-aging internal-friction peak (as a function of strain-ageing time and a temperature internal-friction peak (as a function of temperature of measurement) were observed in Al containing 0.6, 0.1 and 0.01 % Cu (f ~ 1 Hz, \( A_\text{f} \sim 10^{-7} \) to \( 10^{-3} \), \( T_\text{p} \sim 25^\circ\text{C} \)) and in Al containing 0.36, 0.1, 0.03 % Mg (f ~ 1 Hz, \( A_\text{f} \sim 10^{-8} \) to \( 10^{-6} \), \( T_\text{p} \sim 50^\circ\text{C}, T_\text{p} \sim -50^\circ\text{C} \)). The specimen was fully annealed and then lightly deformed at room temperature by stretching or by twisting just after "yielding". The aging internal-friction curve at 18°C of 450°C annealed Al-0.5 % Cu (0.8 % elongated) is shown in Fig. 3a (average \( A_\text{f} \): 0.53 to 0.27 \( \times 10^{-9} \)). /7/

The internal friction around this strain-aging peak was found to be amplitude-dependent and to exhibit an amplitude internal-friction peak when measured at a given aging time as shown in Fig. 3b, by letters marked on the curves in Fig. 3a and 3b. The aging internal-friction curve at 24°C of 400°C annealed Al-01 % Mg (slightly stretched) is shown by Fig. 4a (average \( A_\text{f} \): 3 to 1.5 \( \times 10^{-5} \)) and the amplitude curves corresponding to various aging time are shown in Fig. 4b. /9/

The fact that the anomalous internal friction previously observed in Al-0.5 % Cu can also be observed in Al-0.1 % Mg excludes any possibility of explaining the anomalous internal friction in terms of a precipitation process which cannot occur in Al-0.1 % Mg in the temperature range of measurements.

II. The Cottrell atmosphere-dragging model

An atmosphere-dragging model of internal friction was suggested the first time in 1949. /4, 5/ The fundamental idea is that when the dislocation drags its atmosphere to move with it, an extra resistance is exerted on the movement of the dislocation and gives rise to an additional Q^-1. In low-frequency measurements, the loss due to free motion of dislocations is small, so that Q^-1 is small when the dislocation escaped from its atmosphere. The atmosphere dragging is assumed to be a stress-assisted relaxation process with a relaxation time \( \tau \) depending on temperature \( T \), dislocation velocity \( \mathbf{v} \) (or stress \( \mathbf{\sigma} \)), strain amplitude \( A_\text{f} \), concentration \( C_\text{d} \) of the solute atoms interacting with the dislocations, the migration mode of the solute atoms (long or short range \( \mathbf{\sigma}_\text{d} \) in the lattice or along the dislocation core), etc. Thus various types of internal friction peaks can be observed under suitable conditions: temperature peak, amplitude peak and aging peak \( (C_\text{d} \text{ changes in the process of aging}) \).

The simplified atmosphere-dragging model described above met several difficulties in quantitative respect. /8/ (1) The distance that the dislocation can drag the atmosphere along with it under the stress applied during internal friction measurement is too small. Calculations basing on the data of internal friction measurements with Al-0.5 % Cu showed that the maximum distance of the dislocation movement is only \( 2 \times 10^{-9} \) cm. This is only about 0.07 b, which is unreasonable. (2) In order that the atmosphere can be dragged to move along with the dislocations, the solute atoms constituting the atmosphere must have a diffusion coefficient several order of magnitude larger than the
usual value. Assume that the atmosphere was dragged along to move an average distance of one \( b \) during the relaxation time \( \tau \) of the internal friction measurements, e.g., assume the migration distance of copper solute atoms at the optimum temperature of the internal friction peak (300 K) to be \( b = 2.36 \times 10^{-8} \) cm, then the diffusion coefficient of the copper solute atoms should be \( 2.5 \times 10^{-15} \) cm\(^2\)/sec. But the diffusion of copper in normal lattice of Al is only \( 2 \times 10^{-5} \) cm\(^2\)/sec, which is \( 10^{10} \) times smaller. (3) The critical stress necessary to move the dislocations dragging the atmosphere along with the critical speed as calculated theoretically is several hundred times greater than the observed value. If the observed peak amplitude of the amplitude internal friction peak corresponds approximately to the stress \( \sigma_c \) necessary for the dislocation to escape from its atmosphere, then \( \sigma_c = 4 \times 10^{-6}/\mu \) according to internal friction data. Theoretical calculations basing on Cottrell atmosphere dragging model showed that \( \sigma_c \approx 9 \times 10^{-4}/\mu \) which is about 200 times larger than the value determined by internal friction measurements.

III. The Kink Draging Model

In order to meet the difficulties concerning the Cottrell atmosphere-dragging model described above, a kink dragging model was proposed on the basis of the kink concept developed by Seeger and collaborators. /13/ The basic assumption of this model is that in order to be able to observe the anomalous internal friction phenomena, a certain number of kinks must exist on the dislocation lines. Such kinks can be geometrical or can be formed on "fresh" dislocations produced by cold working. The motion of a dislocation line in a direction perpendicular to itself can be achieved through the sidewise motion of the kinks, so that the difficulty concerning the displacement of the dislocations can be taken care of. And that the critical stress necessary to drag the solute atom by the moving kink with the critical speed should be much smaller than that dragging by moving dislocations.

The kink dragging model suggested can be illustrated by Fig. 5. /8, 11/

Consider that a solute atom is originally situated at the position \( 1' \) at the end of the kink. Under the action of an alternating stress along the direction perpendicular to the dislocation line), the kink moves sidewise to and fro in the direction of the dislocation line. During the first half cycle of vibration, the kink moves from its initial position \( 1' \) to the successive positions \( 2', 3', 4', ... 9', 10' \) in its sidewise motion as shown in Fig. 5. In order to accommodate the requirement of the stress field of the kink, the solute atom migrates from its initial position \( 1' \) to the successive positions \( 2', 3', 4', ... 9', \) and eventually migrates to the position \( 10' \) when the kink is in its position 10. This means that the solute atom has thus been dragged by the moving kink through \( b \). It is to be pointed out that the solute atom lies always on the kink while the kink executes its sidewise motion. The solute atom migrates thus always along the dislocation core so that its migration can be much faster than in the lattice.

IV. Recent Experimental Results

Anomalously amplitude-dependent internal friction peaks accompanying aging peak and temperature peak were observed recently in Al-0.12 wt \% Mg after the specimen was subjected to an ingenious procedure of mechanical and thermal treatment. /14/ The height of the peak can reach 0.1 or more, which is one order of magnitude higher than those observed previously.

An Al-0.12 \% Mg specimen (cold-worked to 84 \% RA) was annealed at 350°C for 1 h and was then twisted at 21°C to \( \pm 0.3 \% \times 2 \). Internal friction measurements were taken during the process of aging at 21°C. The amplitude peaks at some chosen aging times is shown in Fig. 6. It is seen that the high-amplitude side of the peaks decreases slowly and stays at a high value. The specimen aged at 21°C was annealed at an
elevated temperature and internal friction measurements were taken starting from 130°C with descending temperatures. A temperature internal friction peak was observed around 100 to 50°C. Fig. 7 shows the amplitude curves corresponding to the temperature points marked on the curves. The internal friction is extremely high and the high-amplitude side of the amplitude peaks decreases rapidly and continuously to reach a very small value. It is seen that the peak of the amplitude curve shifts considerably toward lower amplitudes with an increase of the temperature of measurement.

An Al-0.12 % Mg specimen (cold-worked to 84 % RA) was partially annealed and twisted at 18°C to $0.3 \times 2$. It was aged at 18°C and then annealed at an elevated temperature and internal friction measurements were taken with ascending temperatures up to 240°C and then with descending temperatures. A peak appeared around 60°C. The amplitude curves corresponding to the temperature range from 94 to 32°C are shown in Fig. 8. The high-amplitude side of the amplitude peaks decreases rapidly to reach a very small value, but it is to be noticed that the peak shifts toward higher amplitudes with an increase of the temperature of measurement which is quite different from that shown in Fig. 7.

Recently, internal friction measurements were taken by Q. Tan of our laboratory on Al-0.02 wt % Mg single crystals. One single crystal was cold-drawn to 36 % RA, annealed at 300°C for 1 h and then twisted at 10°C to ±0.4 %. Internal friction measurements ($f = 1.2$ Hz) were taken during the process of aging at 10°C. The amplitude curves at some chosen aging times is shown in Fig. 9. It is seen that these amplitude peaks are similar to those shown in Fig. 6 for polycrystalline specimen in that the high-amplitude side of the curve decreases slowly and stays at a high value.

The specimen was then aged at room temperature for 3 days and annealed at 300°C for 1/2 h. Three internal friction peaks (Ag = $2 \times 10^{-5}$) appeared at 217 (P3), 128 (P2) and 67°C (P1) as shown in Fig. 10. It is to be noticed that the modulus ($-\mu$) behaves anomalously around P1 and P2. Fig. 11 shows the amplitude curves corresponding to the temperature points (1 to 13) marked on the curves. It is seen that the amplitude curves 1, 2, 3 corresponding to the high-temperature side of P3 shift toward lower amplitudes with a decrease of temperature, whereas the curves 4, 5, 6 corresponding to low-temperature side of P3 shift toward higher amplitudes with a decrease of temperature. The amplitude curves corresponding to the temperature region of the lower temperature peaks P2 and P1 (curves 7–13) is quite diversified. It seems that there is a transition between these two kinds of amplitude curves.

The appearance of several temperature–internal friction peaks exhibiting anomalously amplitude dependent effect has also been observed in polycrystalline Al-0.12 % Mg. The amplitude curves corresponding to the whole temperature region of these peaks are anomalous in the sense that the high-amplitude side of the amplitude peak decreases rapidly similar to those shown in Fig. 7 and Fig. 8. However, the amplitude curves corresponding to the higher temperature region shift toward higher strain amplitudes with an increase of temperature. On the contrary, the amplitude curves corresponding to the lower temperature region seems to shift toward lower strain amplitudes with an increase of temperature.

It is to be pointed out that in the temperature region where the amplitude peaks shift to higher amplitudes with an increase of temperature, the modulus curves always show an anomalous behavior in that the modulus decreases with a decrease of temperature.

V. Discussions

In 1966 and afterwards, amplitude internal friction peaks were observed in Al-Zn and Al containing a small amount of impurities in INSA de Lyon /15/, in α-Zr (containing oxygen) and MgO by Ritchie et al. in
They interpret their results in terms of Blair, Hutchison and Rogers theory based on Teutonico, Granato and Lücke model for the thermally assisted unpinning of dislocations. This theory requires that the amplitude curves should shift towards lower amplitudes with an increase of temperature. It is interesting that amplitude peaks have also been observed in high-purity metals (polycrystalline and single crystal): Stradelmann and Benoit in high-purity Ag, Grau and Schultz in high-purity Mo crystals, and Su and Kë in 99.999 Al single crystal. This means that the amplitude peak is originated not only from the breakaway of the dislocation from point defects (intrinsic or extrinsic), but can also arise from the break down of a dislocation structure.

Now let us confine ourselves to the amplitude peaks associated with the interaction of solute atoms (Cu, Mg) with dislocations in f.c.c. metals (Al). Any realistic model should be able to explain the following characteristics of the amplitude peak:

1. There are two types of amplitude peaks: (a) First type: the high-amplitude side of the peak decreases slowly and stays at almost constant high value. (b) Second type: The high-amplitude side of the peak decreases rapidly to reach a very small value.

2. In the second type of the amplitude peaks, there are: (a) The peak shifts to lower amplitudes with an increase of the temperature. (b) The peak shifts to higher amplitudes with an increase of temperature. In such occasions, the modulus curve always shows an anomalous behavior.

3. Several temperature peaks appeared in the temperature range of 50°C—200°C (f = 1 Hz). The position and the height of these peaks are very sensitive to the previous treatments on the specimen.

As is shown in § III, a model basing on the long range interaction of dislocation-solute atom interaction, such as the Cotrell-atom atmosphere dragging model, does not give a quantitative explanation to the experimental facts. So we can only turn to models in terms of dislocation kinks with consideration only on the short-ranged interaction of the solute atoms and the dislocations. The distribution of the solute atoms with respect to the dislocations can be shown schematically as in Fig. 12. The twisting on the specimen at room temperature causes the dislocations to be torn away from the pinning solute atoms as shown in Fig. 12a. During the aging at room temperature, some solute atoms come back to pin the straight part of the kinked dislocation as shown in Fig. 12b. The concentration of the pinning points on the dislocation is very low so that dislocation unpinning can occur easily during the internal friction experiment. The amplitude peaks corresponding to these cases are those shown in Figs. 3b, 4b, 6 and 9 which can be explained in terms of a dislocation unpinning model as has been done in the literature.

When the twisted specimen was heated to an intermediate temperature such as 250°C or so, more solute atoms will migrate to the dislocations, and the dislocation was pinned not only at the straight parts but also at the kinks as shown in Fig. 1c. Such a distribution may be maintained when the temperature is lowered during the internal friction measurements. However, when the twisted specimen was heated to a still higher temperature such as 350°C or so, some of the solute atoms will leave the dislocation because of thermal agitation. The kink on the dislocation will be depleted of solute atoms the first because the binding energy between solute atom and the kink is much smaller (only about 10%) than that with the straight part of the dislocation. The distribution can then be shown as in Fig. 12d.

For the distribution shown in Fig. 1d, the solute atoms can migrate in a transverse direction according to the process shown in Fig. 5. This is mainly a kind of stress-assisted migration and the shift of the amplitude peak with an increase of temperature of measurement is not definite and sometimes more or less shifted to higher amplitudes.
For the distribution as shown in Fig. 12c, the solute atoms on the kinks can diffuse in a longitudinal direction during the sidewise motion of the kinks. Meanwhile, the solute atoms on the straight parts of the dislocation can migrate in a transverse direction as shown by the distribution in Fig. 12d. Consequently, two internal friction peaks may appear simultaneously (cf. Fig. 10).

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Fig. 1. Internal friction curves versus temperature of cold-worked (95 % RA) Al-0.5 % Cu (partially annealed at various strain amplitudes.)
Fig. 2. Amplitude curves for the internal friction in the region of the temperature peaks shown in Fig. 1.

Fig. 3a. Aging curve at 18°C of 450°C annealed Al-0.5 % Cu (0.8 deformed).

Fig. 3b. Amplitude curve corresponding to the letters marked on the aging curve of Fig. 3a.

Fig. 4a. Aging curve at 24°C of 400°C annealed Al-0.1 % Mg, slightly deformed.

Fig. 4b. Amplitude curves corresponding to the numbers marked on the aging curve of Fig. 4a.
Fig. 5. Transverse migration of a solute atom in the dislocation core through the sidewise motion of a kink.

Fig. 6. Amplitude curves corresponding to various aging times at 10°C of twisted Al-0.12% Mg. Curves 1, 2, 3, 4, 5: 23, 43, 59, 94 and 221 min.

Fig. 7. Amplitude curves corresponding to various temperatures of measurement of twisted Al-0.12% Mg annealed at 350°C. Curves A, B, C, D, E, F: 74, 60, 51, 41, 29, 20°C.

Fig. 8. Amplitude curves corresponding to various temperatures of twisted Al-0.12% Mg annealed at 250°C. Curves A, B, C, D, E, F: 32, 52, 72, 81 and 94°C.

Fig. 9. Amplitude curves corresponding to various aging times at 10°C of twisted Al-0.02% Mg single crystal.

Fig. 10. Internal friction and modulus curves versus temperature of a slightly twisted and aged Al-0.02% Mg single annealed at 300°C.
Fig. 11. Amplitude curves for the internal friction in the region of the temperature peaks P1, P2 and P3 shown in Fig. 10.

Fig. 12. Distribution of the solute atoms with respect to the dislocations. (a) after twisting. (b) After aging. (c) After heating to an intermediate temperature. (d) After heating at an elevated temperature.