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INTERNAL FRICTION AT kHz-FREQUENCIES IN SUPERCONDUCTORS NEAR THE CRITICAL TEMPERATURE

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Abstract.- An internal-friction peak, generally 0.1-1.0K wide, independent of frequency and amplitude, centred at T_c , and associated with the presence of dislocations, has been reported for lead, tantalum, niobium and other metals and alloys. Its characteristics are shown to be explicable in terms of a hysteretic loss arising from the enhancement of the background internal friction, due to the association of edge dislocations with filaments of superconducting phase.

1. **Introduction.**- An internal-friction peak, occurring close to the critical temperature T_c has been observed in several metals and alloys (e.g. Postnikov et al. 1973, 1974, 1975). Its salient features, exemplified by the peak obtained with reeds of niobium 1-200 μm thick, vibrating at strain amplitude of about 10^{-6} at 50-2500 Hz, shown in figure 1, are as follows.

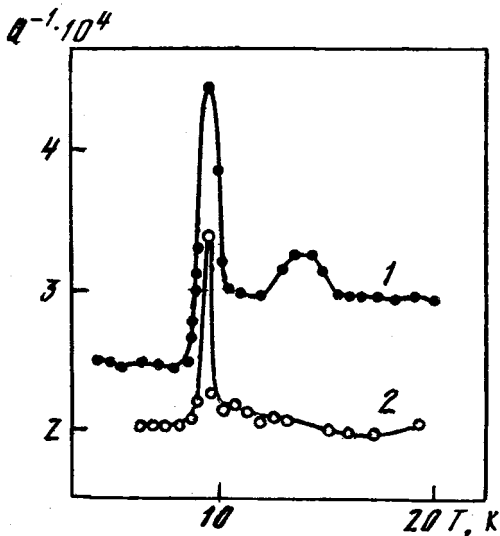


Fig. 1: The internal-friction peak in polycrystalline niobium ($T_c = 9.26\text{K}$) at 4.4 kHz in heavily rolled foil (1), and in the same material after annealing for one hour at 1800K (2). (From Postnikov et al.1973).

Within the domain of variables used the internal friction, Q^{-1} , appeared to be independent of foil thickness, trace impurities, amplitude and frequency in the materials studied, including Pb,Ta,Nb, as well as Nb-Pi and Pb-In alloys. The peak seems to be centred on T_c , as may be seen in figure 1 ($T_c = 9.26\text{K}$). In lead

(Postnikov et al. 1973) the tails of the peak merge into the background at about 6.0 and 8.0K ($T_c = 7.23$ K). Also, on changing the transition temperature by about 1.3K by the application of a magnetic field the peak in lead was found in its new position at 5.9K to be in every respect indistinguishable from that in the initial one ($H = 0$).

In their paper of 1975 Postnikov et al. show that on increasing the frequency of vibration of polycrystalline vanadium reeds from 1 to 6 kHz the peak height diminished by about 20%, but it increased somewhat in absolute value in polycrystalline tantalum. The peaks were narrower at 6 than at 1 kHz, and also slightly lower in both cases if the background level was taken as reference. These effects are relatively small, and are probably due to more effective pinning of dislocations by impurities at the higher frequencies. We shall here not consider them further.

In general there appeared to be a correlation between peak height and the level of the background internal friction. Thus deformation by rolling lead to an increase in the width and height of the peak, at the same time resulting in a rise of the background level (e.g. figure 1).

A model proposed by Postnikov et al. (1975) to account for the observations is based on the attenuation of sound propagating in a crystal along the direction of an array of parallel superconducting filaments, each aligned with a dislocation. Their results may be summarised by

$$Q^{-1} \propto \ell_F, \quad \Delta T/T_c \propto (N/\omega)^{1/2} / \ell_F, \quad (1)$$

where ℓ_F is the mean free path of the Fermi electrons (approximately proportional to T^{-1}), ΔT is the width of the peak (the latter occurring at a temperature somewhat higher than T_c), N is the dislocation density, and ω the frequency of vibration of the specimen. Eq.(1) implies a strong dependence of Q^{-1} and of ΔT on temperature, the lack of a dependence of Q^{-1} on N , and a fairly pronounced effect of N and ω on the peak width. These requirements are at variance with observations. Also, the model does not allow for any correlation between the peak height and the level of the background internal friction.

In the present work we outline a model in which the association of edge dislocations with superconducting filaments results in the enhancement of the frequency and amplitude-independent background internal friction. To this end we shall first show that such a hysteretic background-loss is to be expected to occur at acoustic and subsonic frequencies at strain amplitudes not exceeding about 10^{-6} , i.e. when dislocation-breakaway from pinning points as visualised in one variant of the well-known model of Granato and Lücke (1956) may be assumed not to take place.

2. The Background Internal Friction.— Referring to a dislocation segment of length ℓ pinned at its ends, and bowing under a shear stress τ ($= Gb/2R$), with the maximum displacement of the arc from the initial, straight, position equal to x , the work expended in the incremental expansion of the arc on increasing the shear stress is

$dW \approx \frac{1}{2}(\tau b \ell) dx = (2\tau \ell^3/G) d\tau$, the line energy having been taken equal to $\frac{1}{2}Gb^2$. Thus, neglecting lattice friction, the energy required to expand the segment from its position at zero stress to that attained as the stress assumes the maximum value, at $\tau = \tau_0$, is equal to $\tau_0^2 \ell^3/G$.

At the frequencies considered the dislocation will return to the unexpanded state with negligible momentum at the end of the next quarter-cycle of the forced vibration imposed on it by the oscillating crystal. In the course of its near-isothermal return motion to the initial position the difference in energy between the states at $\tau = \tau_0$ and $\tau = 0$ is lost to the lattice. Thus, for a complete cycle and n segments per unit volume, the loss would be $2n(\tau_0^2 \ell^3/G)$ and, writing $N = n\ell$ for the density of vibrating dislocations, one obtains

$$Q^{-1} = (\Delta W/2\pi W) \approx \alpha N \ell^2, \quad (2)$$

where α is the usual orientation factor. With reasonable values, e.g. $N = 10^7/\text{cm}^2$ and $\ell^2 = 10^{-10} \text{ cm}^2$, $\alpha = 0.1$, one has $Q^{-1} \approx 10^{-4}$, which is of the correct order of magnitude.

3. Dislocations in the Intermediate Phase.- In 1963 Webb showed that, due to their non-uniform stress-fields, dislocations would be expected to stabilise the superconducting state locally. Close to T_c only dislocations with a hydrostatic stress-field would be effective in pinning, e.g. superconducting filaments, and we shall therefore concern ourselves here only with "edges".

Seraphim and Marcus (1962) obtained general relations for the effect of stress on the critical field, considering in particular the n-s transition in tantalum and tin. They found that, for the two metals respectively, near T_c , $\partial H_c/\partial p \approx -9.10^{-4}$ and -7.10^{-3} gauss/bar with corresponding values of dT_c/dp equal to -3.10^{-6} and -5.10^{-5} K/bar.

Now, up to a few interatomic spacings from the centre of a positive edge dislocation the hydrostatic stress-field above its slip plane is readily shown to be of the order of $-0.1G$, and of equal magnitude, but opposite sign, below the glide plane. With $G \approx 7.10^5$ bar for tantalum, and 2.10^5 bar for tin, a rough estimate of the change in the transition temperature in a small tubular volume above the dislocation then yields $\Delta T \approx -0.2K$ and $-1.0K$ respectively.

On complying with Webb's results, the sign of T_c should be reversed for similar regions below the slip plane. Thus, according to the "macroscopic" treatment of the effect, the dilated regions near the cores of the dislocations should stay normal to a significant fraction of a degree below T_c , while superconducting filaments of diameters of the order of the coherence length would be retained in association with edge dislocations up to $T_c + \Delta T_c$. (At $T \ll T_c$ one would however expect all stresses to stabilise only the s-state (Webb 1963)). Local retention of a filamentary form of intermediate phase above, as well as below, T_c could thus account for the observed near-symmetry of the peak around T_c ; in the model of Postnikov et al. (1975) the

peak would be expected to lie above T_c .

4. The Internal-Friction Peak.- The common feature in the association of the dislocations with either component of the mixed phase, of particular importance here, is the existence of a boundary sheath around each filament, typically of width $\delta \approx 10^{-4} - 10^{-5}$ cm, depending on the local coherence length. In bowing-out at acoustic frequencies, a dislocation would induce parallel bowing of the filament, increasing its own length, and also that of the sheath. The energy per unit area of envelope is about $(H_c^2/8\pi)\delta$ (viz. Tinkham 1975), so that for a length of 1 cm, taking $\delta \approx 2r = 5 \times 10^{-5}$ cm and $H_c = 824$ gauss (Ta), one obtains for the line energy 3×10^{-4} erg, i.e. about 2×10^8 eV. Now, taking for the dislocation energy per unit atomic spacing (Ta) $\frac{1}{2}Gb^3 \approx 10$ eV, the line energy would be approximately 3×10^8 eV, so that, allowing for the rather rough approximations, both energies can be seen to be of the same order of magnitude.

On proceeding as in the derivation of equation (2), one now obtains

$$Q_{T_c}^{-1} = \alpha N L^2 (1 + \beta f) = Q^{-1} (1 + \beta f), \quad (3)$$

where β is the ratio of the line energies of dislocation and sheath, and f the fraction of oscillating dislocations of edge type. Except at rather small strains, the latter type will predominate in deformed metals (Essmann and Mughrabi 1979), so that f as well as βf would be expected to be of order unity; in figure 1 the peak at T_c is in fact seen to be about twice as high as the background level.

5. Conclusions.- The principal, observed, characteristics of the peak, particularly its independence of temperature and frequency, its width, and the influence of plastic deformation on the peak height, particularly through the product NL^2 (Spears and Feltham 1972), are explained by the present model. Equally it accounts for the observed correlation of the background internal friction with the peak (eq.3), and leads to correct estimates of the peak width, in terms of a narrow temperature zone centred on T_c within which dislocations stabilise filamentary structures of the intermediate phase. The model also accounts for the widely observed frequency independence of the background internal friction of metals in the n-state, and for the inapplicability of the vibrating-string model to near-isothermal, periodic displacement of dislocations.

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