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DYNAMIC DISLOCATION DAMPING IN METALS

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Abstract. - The simultaneous measurements of the amplitude independent damping and modulus defect in the copper and lead single crystals are performed within the temperature range from 4.2 K to 300 K (Cu) and from 4.2 K to 10 K (Pb) at 5-15 MHz. It is found that the dislocation internal friction in copper is determined by the superposition of two energy loss contributions: dynamic loss caused by the viscous dislocation drag and the relaxation one caused by thermoactivated dislocation motion. The dynamic loss contribution was singled out, and the temperature dependence of the damping constant $B$ is obtained. The $B(T)$ dependence in Cu is discussed in terms of the existing models of the dynamic dislocation damping. By using the superconducting transition in lead the strong evidence is obtained that the damping constant $B$ at low temperatures is determined by the electron-dislocation interaction.

Introduction. - According to the theoretical predictions, the dislocation dynamic damping in metals, characterized by the damping constant $B$, is determined by the phonon-dislocation and electron-dislocation interactions. To obtain the value of $B$ the amplitude independent dislocation internal friction is usually measured, and the results are analyzed in the terms of the Granato-Lucke string model [1]. At present there is a number of mechanisms proposed to describe the dislocation interactions with phonons and electrons. The best way for testing the theories is to study the dislocation damping under conditions of controllable varying of the elementary excitation density in crystal. For example, one can change the phonon density by the temperature varying, and the free electrons density by means of the superconducting transition. However, the experimental realization of that programme has met some difficulties (see, e.g. in case of Cu [2,3]) which has not allowed one to make unambiguous conclusion about dislocation interaction mechanisms involved. These difficulties have been overcome in [4,5]. The authors showed, that the inexplicable behavior of $B(T)$ observed in [2,3] for Cu was due to the fact that the high frequency dislocation amplitude independent damping was determined not only by the dynamic, as has been accepted previously, but rather by the combination of the dynamic and relaxation
types of dislocation damping.

The paper reports on the detailed experimental investigation of the damping constant $B$ temperature dependences in the copper and lead single crystals under the controllable conditions.

**Experimental Method.** - The simultaneous measurements of the amplitude independent dislocation damping and modulus defect in the copper and lead single crystals are carried out within the temperature range from 4.2 K to 300 K at 5–100 MHz for Cu and within 4.2 K to 10 K at 5–15 MHz for Pb by the resonance technique [6]. In order to introduce fresh dislocations the Cu specimens with [III] orientation were compressively deformed by 0.1 to 0.5% in a testing machine through the special device to keep the specimen faces parallel. To stabilize the dislocation structure the measurements were performed in 1.5–2 hours after the deformation. Then the specimen was placed into the cryostat where the measurements of $\gamma$ and $\frac{\Delta M}{M}$ were carried out. To single out the dislocation contribution in the total energy loss the specimen was $\gamma$-irradiated from Co$^{60}$ up to the dose $8.10^8$ rad that corresponds to the complete pinning. It is shown, that the $\gamma$-irradiation dose applied does not influence the non-dislocation contributions to the total loss. The dislocation contribution in $\gamma$ and $\frac{\Delta M}{M}$ is determined as a difference between the values of $\gamma$ and $\frac{\Delta M}{M}$ before and after such $\gamma$-irradiation. The damping constant $B$ is defined from the measurements of amplitude independent internal friction by the wellknown Granato-Lucke relation for $\omega \tau << 1$, where $\tau = \frac{B \xi^2}{K_1 C}$:

$$\gamma = K_1 N \xi^4 \omega B \ , \ \frac{\Delta M}{M} = K_2 N \xi^2 \ , \ B = \frac{K_2 N}{K_1 \omega} \cdot \frac{\gamma}{(\frac{\Delta M}{M})^2} \ , \ (1)$$

where $K_1$ and $K_2$ are the constants; the rest notations are the same as Granato-Lucke used [1]. In order to be confident that the relation $\omega \tau << 1$ is fulfilled, the measurements at the different frequencies were made, and the linear dependence $\gamma$ versus $\omega$ is checked.

The temperature dependence of $B$ defined in the manner described above is shown in the Fig.1 and 2. In Fig.1, three $B(T)$ curves are shown for the case of the same specimen with various mean loop lengths $L$ of a dislocation. In order to obtain in the same specimen various $L$ the specimen was specially irradiated by the different small doses of $\gamma$-irradiation. The measurements were made at 15 MHz. In Fig.2 four $B(T)$ curves are shown for the case of the specimen with the same $L$, but measured at different frequencies. As it seen from Figs.1 and 2, $B(T)$ curves are not monotonous and depend on $L$ and frequency of the measurements. The most differences are seen to observe in the range of 40–100 K. At the same temperature range a stepwise change
The temperature dependence of the damping constant \( B \) calculated from the \( \delta \) and \( \Delta M/\Delta L \) measurements in the same copper specimen with the different mean loop length (\( L \)) of a dislocation arised after the corresponding small doses of \( Y \)-irradiation \( (L_1 > L_2 > L_3) \), \( f=15 \) \( \text{MHz} \).

1(\( L_1 \)), 2(\( L_2 \)), 3(\( L_3 \)) without taking into account the relaxation damping component 4,5,6 the same results obtained by the excluding of the relaxation damping component.

Fig. 1: The temperature dependence of the damping constant \( B \) calculated from the \( \delta \) and \( \Delta M/\Delta L \) measurements in the same copper specimen at the different frequencies. The numbers by the curves denote the measurement frequencies. The points (1 to 4) are obtained without taking into account the relaxation damping component. The points (5-8) are obtained by the excluding of the relaxation damping component.

is found, that is typical for the relaxation type internal friction. This is confirmed by the shift of the \( \Delta M/\Delta L \) step towards the higher temperature when the measurement frequency is increased. Assuming the shift of the \( \Delta M/\Delta L(T) \) is thermally activated, one can estimate the activation parameters of the process involved: \( H=0,035 \) \( \text{eV} \), \( \tau_0 = 10^{-10} \) sec. These are typical for dislocation relaxation process in Cu \([7]\). The observation of the stepwise behavior of the \( \Delta M/\Delta L \) suggests that the dislocation amplitude independent internal friction at high frequencies is determined by the superposition of dynamic and relaxation types of dislocation damping. Knowing the temperature dependence of \( \Delta M/\Delta L \), one can restore the relaxation contribution in \( \delta \) at the different frequencies. It allows one to single out the dynamic contribution to the damping and calculate the new values of \( D(T) \) under the assumption that both contributions are additive. The \( B(T) \) curves obtained by excluding the relaxation damping contribution are shown in Figs.1,2. It is seen, that in this case \( B(T) \) does not depend on the parameters of the dislocation structure and frequency measurements, that should be expected since \( B \) is the fundamental characteristic of material. As one can see, there are two regions in the temperature dependence of \( B \). The first one (20-300 K) depends on
the temperature and is connected with the phonon-dislocation interaction, the second one is temperature independent and can be associated with electron-dislocation interaction. Since $B = B_{ph} + B_{el}$, and $B_{el}$ is considered to be temperature independent \[8\] one can calculate $B_{ph}$ as a difference between the value of $B(T)$ and temperature independent part of $B$. The corresponding plot of $B_{ph}$ is shown in Fig. 3 (the points are indicated by triangles). The theoretical curve of $B_{ph}$ shown in Fig. 3 (solid line) is plotted for the case $\Delta = 0.4$, where $\Delta$ is the experimentally determined value that characterizes the relative contribution of "slow phonon relaxation" mechanism to $B_{ph}$ compared with the "phonon wind" mechanism \[9\]. In the same figure the data of $B_{ph}(T)$ obtained by the direct measurements of dislocation mobility \[10\] are shown. Comparison of these results with the present ones fitted.

Estimation of $B_{el}$ from the experimental data give $B_{el} \sim 1.5 \times 10^{-5}$ dyn.s/cm$^2$ that agrees well with theoretical value of $B_{el}$ for Cu \[8, 11\]. However, the stronger evidence might be the experiments in which one could show that the variation in the electronic system leads to the corresponding changing in $B$. It can be performed by the superconducting transition. Unfortunately, the temperature of the N-S transition in copper crystals is very low, therefore such kind experiments are convenient to carry out in the lead single crystal, where the critical temperature is about 7.2 K. Thus, the amplitude independent damping and modulus defect is investigated in the 99.999% pure (resistivity ratio $\rho_{300K}/\rho_{4.2K} = 4 \times 10^3$) lead single crystals with [110] orientation at 5-15 MHz. In this frequency range the relation $\omega \tau << 1$ has been fulfilled for the specimens used. The idea of the experiment was as follows. As it is seen from (1) if $B = B_{el}$ the decrease of the free electron density caused by the N-S transition will lead to the corresponding decrease of the dislocation damping decre-

![Fig. 3: The temperature dependence of $B_{ph}$ normalized by the Debye temperature $\theta$. Solid line is a theoretical curve for the case of $\Delta = 0.4$ \[9\]. 1(\()$ the present results, 2(\()$ the results of Jassby and Vreeland\[10\].]
ment $\delta$ whereas the value of $\Delta W$ will remain unchanged. It is necessary to point out that unlike copper experiments it is very difficult to single out the dislocation contribution to total damping. Therefore to single out the dislocations contribution to the total damping change the other procedure was used.

![Image](image1.png)

It is illustrated by the Fig. 4. $N_1$ and $S_1$ curves represent the dependences of $\delta$ and $f$ in the $N$ and $S$-states on the voltage amplitude given across the transducer. From Fig. 4 the region of the amplitude independent damping is clearly seen. It is necessary to notice that $\delta$ in the $N$-state is much larger than in the $S$ state whereas $f$ is practically independent of the state. The curves $N_2$ and $S_2$ correspond to the same specimen but subjected to a additional deformation. The magnitude of the dislocation contribution to the damping is proportional to the difference between corresponding values before and after additional deformation. One can see that the modulus defect does not change at the $N$-$S$ transition, whereas the value of the dislocation damping in the $N$-state larger than in the $S$-state. According to (1) it indicates that observed dislocation damping change is actually due to varying of $R$ at the $N$-$S$ transition. It seems to be a strong evidence of the existence of electronic damping of dislocations. The investigation of the temperature dependence of the damping constant $P_{el}$ in lead single crystals (Fig. 5) shows that in the $N$-state $P_{el}$ does not depend on temperature, and in the $S$-state $P_{el}$ varies proportionally with the free electron density. This coincides with
the predictions of the Kravchenko theory proposed to explain the mechanism of the electron-dislocation interaction [11].

References