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AC LOSSES OF THE ELECTROMAGNETIC ENERGY AND CRITICAL CURRENT DENSITIES IN SUPERCONDUCTING Pb-In ALLOYS

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AC losses of electromagnetic energy in cylindrical samples of Pb-In alloys of different contents and different surface states were determined. In the Meissner state the strong influence of the trapped magnetic flux on losses was observed. The values of the critical current densities were calculated. The results obtained are in good agreement with the generalized critical state model.

1. Introduction

Knowledge of the loss mechanism in type II superconductors is very important for designing superconducting devices working in alternating magnetic and electric fields. It is possible to distinguish losses occurring in the Meissner state (so-called surface losses) from the losses occurring at a magnetic field strength exceeding the value $H_{c1}+\Delta H$ (so-called volume losses). The value ΔH is the parameter of screening of the sample interior by surface currents.

Surface losses are caused mainly by the existence of surface irregularities in which the external magnetic field strength locally exceeds the value H_{c1}. A detailed analysis of this phenomenon was made by Melville [1]. Volume losses may be obtained quantitatively as the basis in the critical state model given by Bean [2] and London [3]. According to this model losses are directly proportional to the third power of the amplitude of the applied magnetic field and inversely proportional to the critical current density, assuming, that the critical current density is constant and independent of the external magnetic field strength. In the so-called generalized critical state model introduced by Dunn and Hlawiczka [4] as well as Fournet and Mailfert [5], who included the influence of the screening

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parameter ΔH, the expression for the energy loss per surface unit and per cycle takes the form:

$$P = \frac{2}{3}\frac{\mu_0}{J_c}[(H_m-\Delta H')^3+3\Delta H(H_m-\Delta H')^2], \tag{1}$$

where $\Delta H' = H_{c1}+\Delta H$, H_m — the amplitude of the external magnetic field strength and J_c — critical current density. This dependence is valid for values of the magnetic field strength amplitudes $H_{c1}+\Delta H \leqslant H_m \leqslant H^*$, where H^* is the magnetic field strength at which the magnetic flux inside a superconductor reaches the center of a sample.

In our investigation losses in Pb–In alloys, with different parameters influencing the losses, were determined and the results obtained were compared with the generalized critical state model.

2. *Measurements technique*

A method similar to the one described by Penczyński [6] was used for measuring the energy loss. Cylindrical samples were placed in a sinusoidally variable magnetic field parallel to the sample axis. A magnetic field was produced by a copper coil cooled in liquid nitrogen. Average losses per surface unit and per cycle for a cylindrical sample are given by the following relation:

$$P = \frac{1}{2\pi RN}\int_0^T H_m \sin\omega t U(t)dt, \tag{2}$$

where R — sample radius, H_m — external magnetic field strength amplitude, T — oscillation period, $U(t)$ — induced voltage in a pick-up coil with N turns.

After making simple calculations expression (2) takes the form:

$$P = \frac{1}{SNf}H_{rms}U_{rms}, \tag{3}$$

where S — circumference of the sample, H_{rms} — the rms value of the external magnetic field strength, U_{rms} — the rms value of the voltage induced in the pick-up coil and f — frequency of the external magnetic field. The voltage U_{rms}, being in phase with the external magnetic field was measured by means of a lock-in amplifier type PAR HR-8. To compensate for the background component of the measured signal, the compensating technique known from the literature [6] was adopted. Using our apparatus it was possible to measure losses of the order of 10^{-4} μW/cm^2 Hz at a magnetic field frequency of 60 Hz.

3. *Results*

Loss measurements were made on samples having the form of bulk cylinders of diameter 4 mm and length 40 mm, made of alloys of various Pb–In compositions. Lead and indium having a purity of 5 N were used in the preparation of the samples. Before measurements the samples were kept in vacuum at temperatures some degrees below the melting point in order to remove mechanical stresses. Fig. 1 shows the dependence of losses upon the external magnetic induction for the samples: Pb-80% at. In (sample *A*), Pb-40% at. In (sample *B*) and Pb-20% at. In (sample *C*). The value of the exponent in the surface loss dependence upon the external magnetic field strength is conditioned mainly by the quality (roughness) of the sample surface. For the sample *C*, the surface of which was polished mechanically and next chemically in a water solution containing $HF + H_2O_2$ this exponent is the lowest and is about 3, for the sample *B* having surface polished mechanically only, it is 4. For the sample *A* with the surface unpolished and polished mechanically, this exponent is about 7 and 4 respectively. Curves for the sample *A* reveal also that the width of the transition range from the surface losses to the volume losses depends strongly on the state of the sample surface. Using relation (1) for the values of the losses obtained from the measurements, it is possible to calculate the critical current density J_c for a given sample. These values are given in the figure caption. Fig. 2 shows the losses for several temperatures of the sample Pb-10% at. In. The temperature dependence of the critical

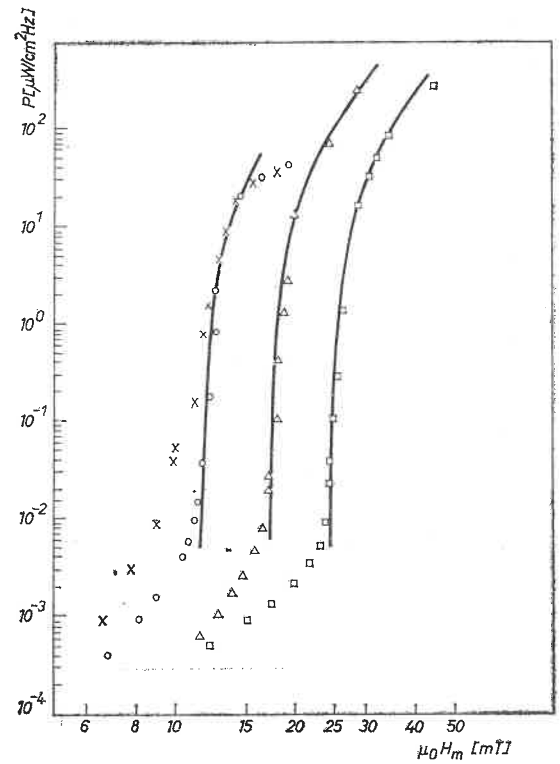

Fig. 1. The dependence of the losses on the external magnetic induction amplitude $\mu_0 H_m$ (× and ○ — sample *A* as received and mechanically polished, respectively, $J_c = 90$ A/cm^2; △ — sample *B* mechanically polished, $J_c = 140$ A/cm^2; □ — sample *C* chemically polished, J_c — 365 A/cm^2; solid lines — evaluated curves according to the relation (1))

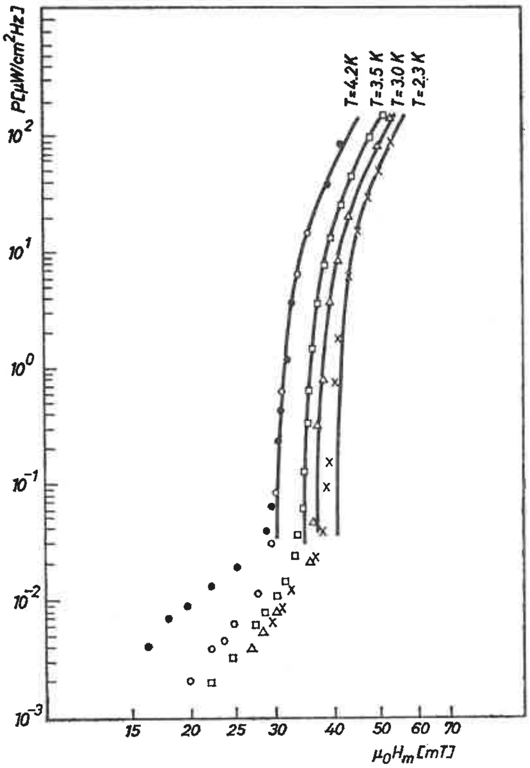

Fig. 2. The dependence of the losses on the external magnetic induction amplitude for different temperatures in Pb-10% at. In sample. ○, □, △, × — virgin state of the sample, ● — with trapped flux

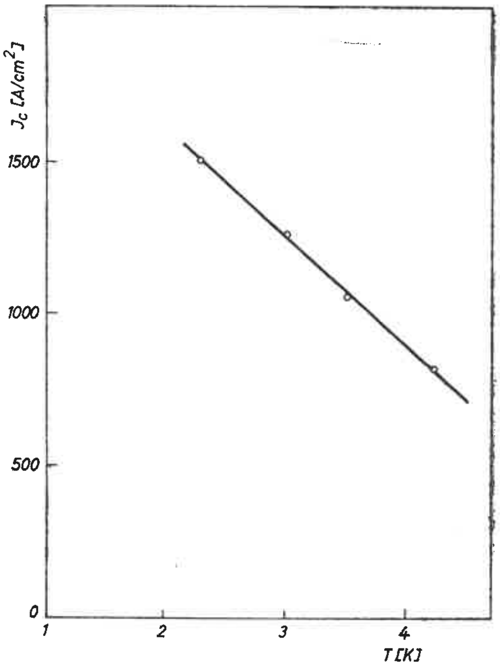

Fig. 3. Temperature dependence of the critical current density in the sample Pb10% at. In

current density for this sample is shown in Fig. 3. Values of losses at low external magnetic field strengths depend strongly on the trapped magnetic flux in the sample. Loss increase caused by this phenomenon at the temperature 4.2 K is shown for example in Fig. 2. At low magnetic field strengths losses in the sample which has been previously cycled into the mixed state are about four times greater than the losses in the sample in the virgin state (i. e. cooled below the critical temperature in the absence of the external magnetic field). The exponent of the surface loss dependence on the external magnetic field is also changing value from about 5 for the sample in the virgin state to 3 for the sample with the trapped magnetic flux.

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