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Size Effect in Impedance of Nb_3Al Superconductor

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We present the results of the impedance measurements in Nb_3Al superconducting polycrystalline alloy vs. temperature and magnetic field. Using these results and applying the size effect model we calculate the flux-flow conductivity of the Nb_3Al superconducting alloy near its critical temperature.

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1. Introduction

One of the basic method of studying superconducting state electrodynamics is the measurement of the complex susceptibility, $\chi = \chi' - \mathrm{i}\chi''$. Results obtained by this method we can correlate with measurement of the impedance, $Z = R + \mathrm{i}X$ ($R \sim \chi''$, $X \sim \chi'$). For the first time, this method was used in Refs. [1, 2]. In these references a maximum in absorption in conventional superconductors (tin, tin-lead alloy) was observed. The authors connect this maximum with the purity and filamentary structure of the investigated material. In Ref. [3] measurements of a defect-free NbTa alloy were carried out. For the description of the maximum, Clem et al. used a model of an average flux-flow conductivity. In Ref. [4] it was proved that the peak in the absorption is connected with eddy currents, like in a normal metal. Furthermore, using the model of average conductivity, it was shown why the peak was not observed in pure materials. In further works [5, 6]

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thermally assisted flux-flow phenomenon (TAFF) was discussed. It was found that this phenomenon occurred between temperature of irreversibility and critical temperature. In our work we used this model to study the flux-flow conductivity in a polycrystalline Nb_3Al superconductor.

2. Experiment

We performed measurements of real and imaginary impedance part of Nb_3Al polycrystalline slab with dimensions $11 \times 7 \times 2$ mm^3. Our sample was placed in a pick-up coil, which had 50 turns of copper wire. The longest edge of the sample was parallel to the ac and dc external magnetic fields. The impedance measurements were carried out by using a high precision RLC-meter (AgilentTechnologies, model 4284A) in the voltage stabilization mode. The coil was supplied by $U_{\mathrm{rms}} \approx 1$ V. The amplitude of the ac magnetic field in the coil was estimated to be not higher than $\mu_0 h_0 \approx 5 \times 10^{-4}$ T. The pick-up coil, with the sample, was placed in the cryostat of the 12 Tesla superconducting magnet. Measurements were carried out at different constant temperatures, which were varied, from 4.2 K to 15.5 K. The ac frequency was 10 kHz. Temperature control was made by a thermocouple, which was placed at the sample surface. External dc magnetic field was swept from zero to 12 T with a rate of approximately 1 T/min and was controlled by a Hall probe.

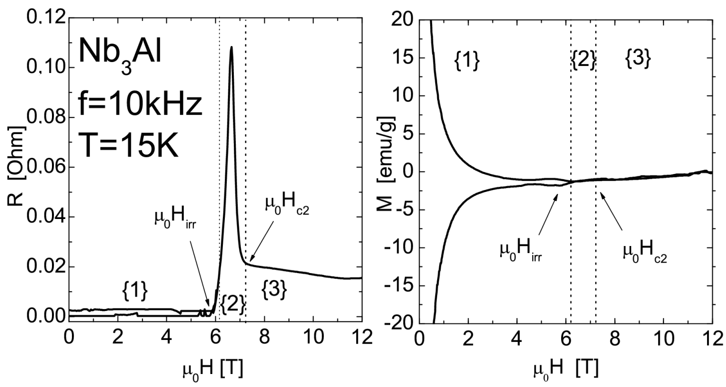

Fig. 1. Left: real part of the impedance of Nb_3Al slab, measured at 10 kHz and $T = 15$ K, right: dc magnetization, measured at the same temperature. {1} critical state region (critical current density is not equal to zero), {2} flux-flow conductivity region (critical current density is equal to zero), {3} normal state region. $\mu_0 H_{\mathrm{irr}}$ and $\mu_0 H_{\mathrm{c2}}$ are irreversibility and second critical field, respectively.

The left part of Fig. 1 shows experimental data of absorption in Nb_3Al sample vs. dc external magnetic field, taken at 15 K. In this figure one can see a maximum of the impedance curve. This maximum is connected with a typical size effect. It occurs when the depth of electromagnetic field penetration is equal to one half of the sample thickness [7]. In the right part of Fig. 1, we present dc magnetization measurements at 15 K. They were carried out by a vibration sample magnetometer. The value of the magnetization is proportional to the average critical current density in our sample. Analyzing Fig. 1, we can divide the investigated region of magnetic field into three parts: {1} region of critical superconducting state (critical current density is not equal to zero), {2} flux-flow conductivity region (critical current density is equal to zero) and {3} normal state region. In regions {2} and {3} the model of the skin size effect can be used. In region {1} the absorption of superconductors can be determined from the critical state model.

3. Model

In this section we calculate impedance of a coil with a type-II superconductor, $Z_{\rm coil}$, in the flux-flow regime. An equation for susceptibility of superconducting slab in TAFF regime is given by the following formula [5, 6]:

$$\chi = \frac{1}{u}\left[\frac{\sinh(u)+\sin(u)}{\cosh(u)+\cos(u)} - u - {\rm i}\frac{\sinh(u)-\sin(u)}{\cosh(u)+\cos(u)}\right], \tag{1}$$

where $u = 2d/\delta_{\rm ff}$, $\delta_{\rm ff} = \sqrt{\frac{2}{\mu_0\omega\sigma_{\rm ff}}}$, $\sigma_{\rm ff}$ — flux-flow conductivity, ω — frequency, $2d$ — slab thickness and μ_0 — permeability of vacuum. In our case, we have field depended flux-flow conductivity, $\sigma_{\rm ff} = \sigma_{\rm ff}(\mu_0 H)$, where $H = H_0 + h$. H_0 denotes the magnitude of the external dc magnetic field, h — magnitude of the external ac field, $h \ll H_0$. In our -analysis, we can use Eq. (1), if we put into it the field dependent flux-flow conductivity, $\sigma_{\rm ff}(\mu_0 H_0) \approx \sigma_{\rm ff}(\mu_0 H)$. The correlation between the impedance of the coil with superconducting sample and the complex susceptibility is given by the following formula (for cylindrical geometry see Ref. [8]):

$$Z_{\rm coil} = \gamma d\omega\mu_0 N^2\left[\chi'' + {\rm i}(1+\chi')\right], \tag{2}$$

where γ is a coefficient connected with a mutual inductance of the coil and finite dimensions of the sample. N denotes the number of turns of the pick-up coil. Using Eqs. (1) and (2), one can obtain the impedance of a coil with superconductor $Z_{\rm coil} = R_{\rm coil} + {\rm i}X_{\rm coil}$:

$$R_{\rm coil} = \gamma N^2\frac{1}{\delta_{\rm ff}\sigma_{\rm ff}}\left[\frac{\sinh(2d/\delta_{\rm ff})-\sin(2d/\delta_{\rm ff})}{\cosh(2d/\delta_{\rm ff})+\cos(2d/\delta_{\rm ff})}\right], \tag{3}$$

$$X_{\rm coil} = \gamma N^2\frac{1}{\delta_{\rm ff}\sigma_{\rm ff}}\left[\frac{\sinh(2d/\delta_{\rm ff})+\sin(2d/\delta_{\rm ff})}{\cosh(2d/\delta_{\rm ff})+\cos(2d/\delta_{\rm ff})}\right]. \tag{4}$$

In Eq. (3) we assume that the absorption of an empty pick-up coil is small in comparison with the absorption of the superconductor.

4. Results

We have calculated resistivity of Nb_3Al slab in the flux-flow regime for two temperatures: $T = 13.4$ K and $T = 15$ K. The results are presented in Fig. 2. The left part of Fig. 2 shows original experimental data, which were obtained following the procedure described in Sect. 2. The right part of Fig. 2 shows resistivity in the flux-flow regime $\rho_{\rm ff} = 1/\sigma_{\rm ff}$. This resistivity was obtained numerically from the formula (3), taking $N = 50$, $\omega = 2\pi \times 10^4$ Hz, and $d = 0.001$ m. The γ-coefficient in Eq. (3), $\gamma = 1.315$, was received using the value of the absorption in the maximum of our experimental curve, where $2d/\delta \approx 2.254$ [6]. The obtained in our procedure value of the normal state resistivity is in good agreement with the value presented elsewhere [9].

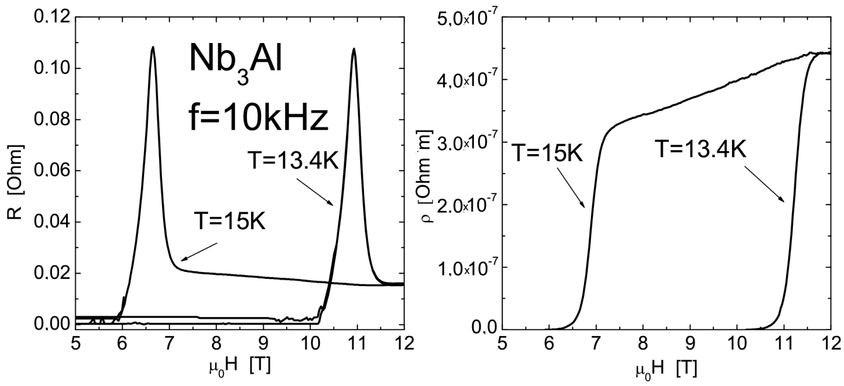

Fig. 2. Left: real part of the impedance of Nb_3Al slab measured at the frequency of 10 kHz for $T = 13.4$ K and $T = 15$ K. Right: flux-flow resistivity obtained from the impedance experimental data, using formula (3), taking $N = 50$, $d = 0.001$ m, and $\gamma = 1.315$.

In order to apply the model presented in Sect. 3 we must calculate the range of magnetic field and temperature, in which the flux-flow damping force dominates the pinning force. Pinning and flux-flow damping forces are determined by formulae [10]:

$$f_{\rm p} = j_{\rm c}B, \quad f_{\rm d} = \eta v_l, \tag{5}$$

where $\eta = \sigma_n B B_{\rm c2}$ — flux-flow damping coefficient ($B_{\rm c2}$ — second critical field), $v_l = E_l/B$ — vortex velocity. The amplitude of E_l we take from measurements of ac voltage on our pick-up coil, $E_l = U/Nl$, where U denotes coil voltage, l — coil perimeter, and N — number of turns. Using Eq. (4) we receive:

$$\left(\frac{f_{\rm p}}{f_{\rm d}}\right)_{\rm max} = \frac{j_{\rm c}(T)BNl}{\sigma_n B_{\rm c2} U}. \tag{6}$$

In the case of our Nb_3Al sample $B_{\rm c2}$ (0 K)=40 T, $\sigma_n = 2.5 \times 10^6$ 1/(Ohm m), $U = 1$ V, $l = 0.018$ m. $j_{\rm c} \approx 10^5$ A/m^2 for $T = 15$ K and $\mu_0 H_0 = 6.1$ T. $j_{\rm c} \approx 3 \times 10^5$ A/m^2 for $T = 12.5$ K and $\mu_0 H_0 = 10.5$ T (critical current density was determined on the basis of dc magnetization data [11]). At the temperature of 15 K and $\mu_0 H_0 = 6.08$ T we obtained $\frac{f_{\rm p}}{f_{\rm d}} \approx 0.055$. At the temperature of

12.5 K and $\mu_0 H_0 = 10.5$ T — $\frac{f_p}{f_d} \approx 0.28$. In the range of temperatures close to the critical one, the critical current density is equal to zero and $\frac{f_p}{f_d} = 0$. For example, $\frac{f_p}{f_d} = 0$ at $T = 12.5$ K and $\mu_0 H_0 > 11.05$ T, as well as at $T = 15$ K and $\mu_0 H_0 > 6.3$ T [11]. According to our estimations, we can state that the peak in the ac absorption curve can be explained taking into account the skin size effect in the flux-flow regime.

5. Conclusions

We used the theory of classical skin size effect for analyzing impedance data near critical temperature in a slab of conventional Nb_3Al superconductor. It is shown that the flux-flow model can be used for description of conductivity in this region. Using numerical calculations, one can obtain from impedance data the magnetic field dependence of the flux-flow conductivity.

Acknowledgments

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