THE DISTRIBUTION OF THE TRANSPORT CURRENT IN A CYLINDRICAL SAMPLE OF TYPE-II SUPERCONDUCTOR IN A LONGITUDINAL MAGNETIC FIELD

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The distribution of the magnetic field produced by the current inside the slot in Pb+23 at % In samples placed in a longitudinal magnetic field was measured by means of a moving Hall probe. It has been shown that the transport current flows only in the surface region up to the magnetic fields close to H_{c2}, which made the critical current density concept rather questionable. Current penetration over the whole cross-section was connected with the appearance of a longitudinal voltage along the sample. The sample with higher pinning had the lower value of critical current. The comparison of measured field distributions with the latest theoretical model was made.

To explain the increase in critical current in a longitudinal magnetic field (compared to perpendicular field) Bergeron [1] suggested that the transport current adopts the force-free configuration in which $J \times B = 0$. To explain the results of his experiments on longitudinal magnetization, Le Blanc [2] accepted the assumptions of two models of magnetization: the Bean model [3] and the Kim et al. model [4]. But still the understanding of the configuration of transport current flow in a type-II superconductor in the presence of a longitudinal magnetic field is rather poor. There are a lot of methods for determining the flux gradient inside the sample. The most common methods of determining J_c (critical current density) are: (*i*) the resistive measurements; (*ii*) DC magnetization measurements; (*iii*) harmonic analysis of a signal induced in a pick-up coil wound around the specimen by a small ripple field superimposed on a much larger DC field; (*iv*) the measurements of total flux by means of a lock-in amplifier and the apparatus as in the previous method; (*v*) measurements of differential magnetization loops and (*vi*) direct measurements of the flux gradient inside the slot in the sample by moving a microprobe there. The last method was most frequently used to measure flux profiles inside the samples placed in an external magnetic field [5]. There are only a few papers [6] where this method was employed

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to measure the transport current distribution. We applied the same method to determine the distribution of the magnetic field produced by the current inside the slot of Pb+23 at% In samples.

Samples 10^{-1} m long and 4×10^{-3} m in diameter were cast in a cylindrical form. In the middle of the sample (lengthwise) there was a slot 3×10^{-4} m wide 4×10^{-3} m long which was parallel to the sample axis. Starting materials employed in prepearing the samples were 5*N* purity lead and indium. At first the Pb+23 at % In alloy was made and then to part of it 4*N* purity silver powder was added to increase the density of pinning centers. The method of preparing samples and checking their quality was described in the previous article [7].

The distribution of the magnetic field inside the slot was measured by means of a Hall probe. It was made from a InSb single crystal having an active area of 5×10^{-10} m^2. The Hall probe was placed in the plane parallel to the sample axis so its voltage was related to the azimuthal component of the magnetic field. The sensitivity of the probe allowed the measurement with an accuracy of 3×10^{-5} T which made it possible to detect the field produced by the current of 1.5×10^{-2} A at a distance 10^{-4} m from the sample axis. The Hall probe was driven by means of a synchronical motor whose movement was transmitted to the probe by means of a worm-gear. The probe position inside the sample might be determined by means of a revolution counter (the probe displacement at a distance of 2×10^{-3} m required about 2000 turns of the counter). When the Hall probe plane was not exactly parallel to the external magnetic field the measurements were made point by point and at every point the voltage on the Hall probe was compensated before the current was switched on. The sample with the coaxial current leads and the mechanism for driving the Hall probe was placed in the bore of a superconducting magnet having field homogeneity not worse than 0.1% in the measuring volume. During all the measurements the voltage along the sample was monitored as well.

In Fig. 1 the magnetization curves obtained by the integrating method for the samples PbIn and PbIn+Ag are shown. The parameters characterizing both samples are: $\mu_0H_{c1} \simeq 12$ mT (obtained from AC losses), $\mu_0H_{c2} = 0.37$ T (it differs by about 3% for both samples), $\mu_0H_c \simeq 55.8$ mT, $\kappa = 4.7$ (determined from the slope of magnetization near H_{c2}), $T_c = 7.01$ K, $R_{300}/R_{4.2} = 2.08$ for PbIn and $R_{300}/R_{4.2} = 1.64$ for PbIn+Ag. All measurements were made at 4.2 K.

The distribution of the azimuthal component of the magnetic field of the current $I = 50$ A as a function of distance from the sample axis are shown in Fig. 2. The plots are made for different values of the reduced magnetic field $b = H/H_{c2}$. It is worth to pay attention to some characteristic features of these plots. First in the pure superconducting state $H = 0$ the surface layer in which the magnetic field produced by the current exists is much thicker than the penetration depth λ. This result may be caused by the slot in the sample. To keep the current density on the sample surface constant the current has to flow partly through the walls of the slot giving deeper field penetration in the slot than in the volume of the sample. Secondly the measured depth of current flows is unchanged even for fields much higher than H_{c1}. The first detectable deviation from the distribution characteristic for a pure superconducting state occurs for the reduced field $b = 0.9491$. An increase

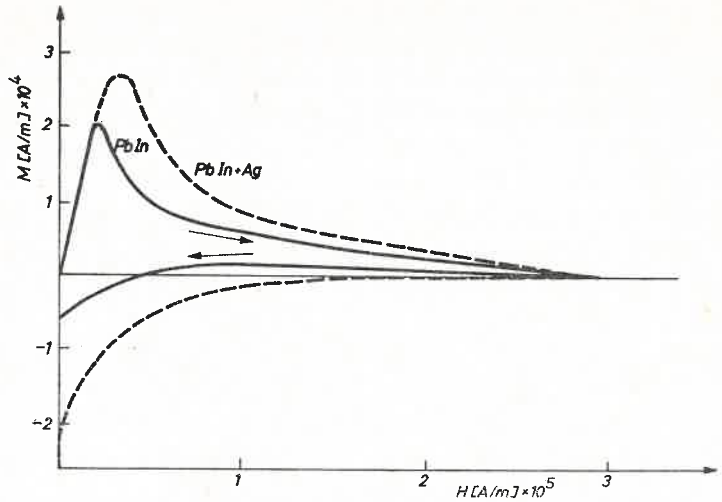

Fig. 1. The magnetisation of PbIn (solid line) and PbIn+Ag (dashed line)

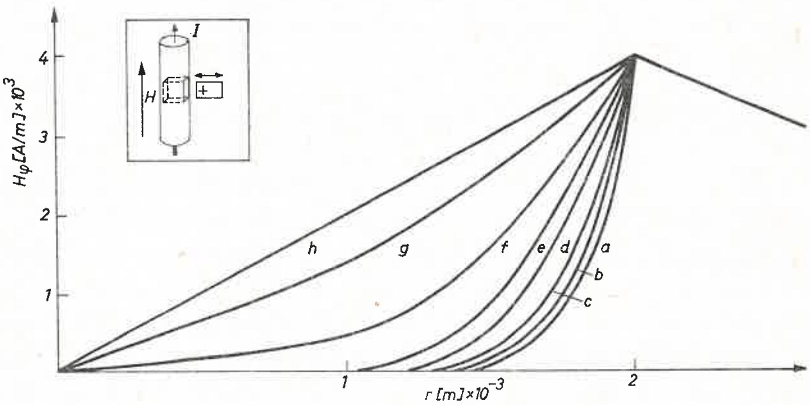

Fig. 2. The distributions of the magnetic field of the current inside the PbIn sample for different reduced magnetic fields: a) $b = 0$; b) $b = 0.9491$; c) $b = 0.961$; d) $b = 0.9735$; e) $b = 0.9783$; f) $b = 0.9837$; g) $b = 0.9897$; h) $b = 0.9945$. The maximal estimated error of measured H_φ is 25 A/m and position of the probe error is about 1 μm

of the external magnetic field causes a deeper current penetration and for the field $b = 0.9837$ the current flows through the whole cross-section of the sample. Such a flow is connected with the appearance of a voltage along the sample. Further increase in the external field causes a more homogeneous current flow and for the field $b = 0.9945$ the current density throughout the sample is constant.

In Fig. 3 the flux profiles for the current $I = 50$ A in PbIn with silver powder for a different reduced magnetic field b are shown. In this sample the layer in which the current flows is thinner than in the PbIn sample. Similar results were obtained by Thorel et al. [8] who found that the current, after reaching its critical value, flows mainly in the surface region of the sample. The authors doubted that the critical current density concept was reasonable as a parameter describing the superconductor. Current penetration to the sample volume starts for fields lower than in the previous sample i.e. for $b = 0.8577$. The whole cross-section is occupied by the current for fields $b > 0.958$. This result is a little surprising,

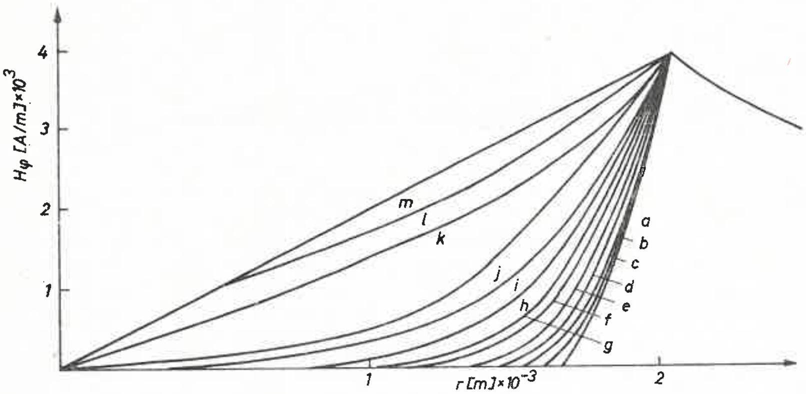

Fig 3. The distributions of the magnetic field of the current inside the PbIn+Ag sample for different reduced magnetic fields: a) $b = 0$; b) $b = 0.8577$; c) $b = 0.8963$; d) $b = 0.9132$; e) $b = 0.9216$; f) $b = 0.93$; g) $b = 0.9412$; h) $b = 0.9473$; i) $b = 0.9524$; j) $b = 0.958$; k) $b = 0.9664$; l) $b = 0.9809$; m) $b = 0.995$

because the critical current for the sample with higher pinning is lower than for the sample without silver powder (the magnetic field of the current reaches the sample axis for a lower reduced field). It seems that this result may be explained by Sugahara's proposal [9]. The flux lines of the external magnetic field entering the sample without pinning remain straight and practically there is not any interaction between the flux and the transport current in the sample. When there are pinning centers inside the sample, entering flux lines bend on it creating profitable conditions for influence with the transport current. Similar behaviour was observed by Kroeger and Schelten [10] when the current flowed in the surface region for the samples with low pinning while for samples with high pinning through the whole volume.

When the sample is placed in a steady external magnetic field the switching of the current on and off for the first time, produces the different Hall voltage than before the operation. Later the Hall voltage is unaffected by switching the current on and/or off. The next such difference occcurred after a change in the external magnetic field provided that during the change of magnetic field strength the transport current was switched on. Such differences in the Hall voltage were unrepeatable. A similar phenomenon was observed by Thorel et al. [8] and was connected with the rearrangement of the vortex structure under the influence of the applied current.

From the measurements of the azimuthal component of the magnetic field of the current the transport current density j_z may be easily evaluated.

$$j_z = \frac{\mu_0}{r} \frac{\partial(H_\varphi \cdot r)}{\partial r} . \tag{1}$$

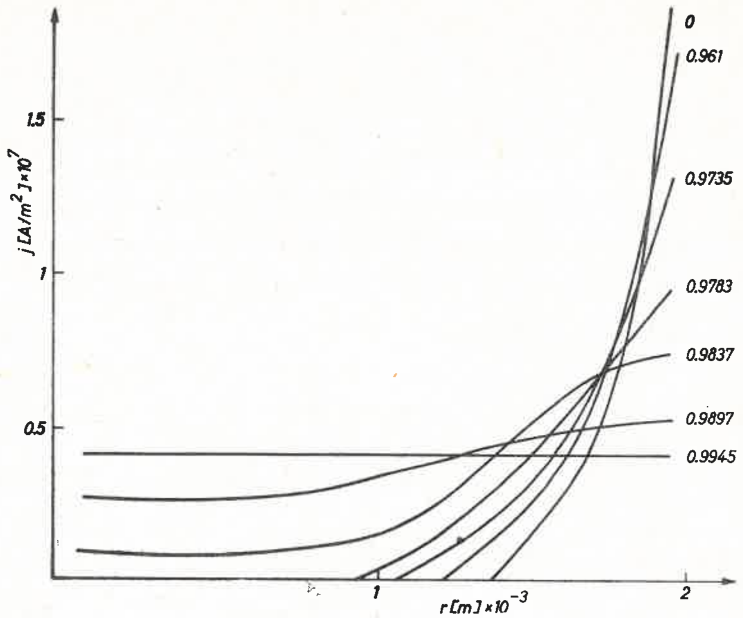

Fig. 4. The current density profiles inside the PbIn sample for different reduced magnetic fields

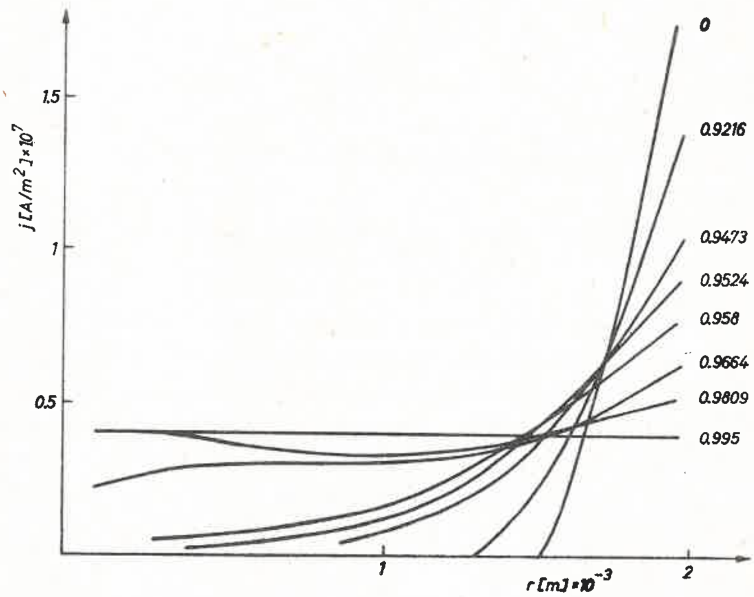

Fig. 5. The current density profiles inside the PbIn+Ag sample for different reduced magnetic fields

Here r is the distance from the sample axis and H_φ — azimuthal component of the magnetic field. The results of such calculations are shown in Fig. 4 and 5 for PbIn and PbIn+Ag, respectively. The curve for $b = 0.9809$ from Fig. 5 shows the strange feature. Near the sample axis the current flows in the same manner as in the normal state. We think that for fields so close to H_{c2} and for the rather large current $I = 50$ A it may be connected with the heating of the sample.

There are a few papers in which the authors were dealing with theoretical calculations of current distribution inside the wire of a type-II superconductor placed in a longitudinal magnetic field. Unfortunately their results are difficult to compare with our results because

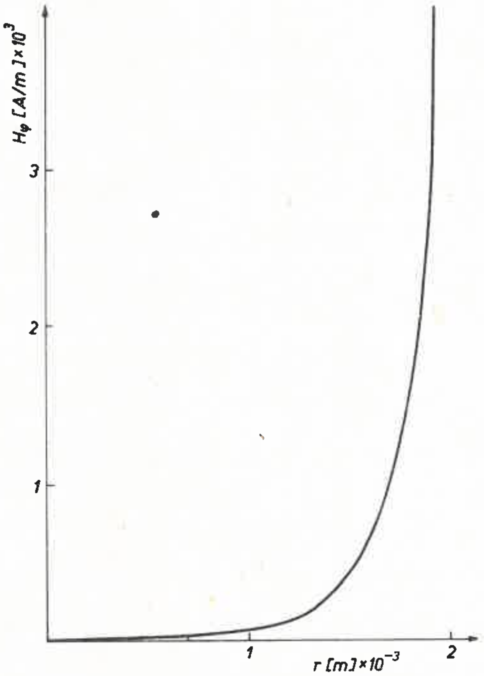

Fig. 6. The plot of theoretical curve (2) for $I = 50$ A, $R = 2\times10^{-3}$ m, $c = 1$, $\beta = 0.018$, $\varkappa = 4.7$ and $\lambda = 4\times10^{-6}$ m

of the different geometries which were examined (slab in longitudinal magnetic field) in [9, 11], nonlinear equations for which it is too difficult to get analytical solutions [12] or the appearance of parameters difficult to obtain experimentally [13]. But in a paper published recently [14] those authors examined, on the basis of the Ginzburg–Landau theory, the ideal type-II superconductor in a longitudinal magnetic field close to H_{c2}. They obtained the expression for the azimuthal component of the magnetic field which may be compared with our results. This expression is

$$H_\varphi(r) = \frac{2I}{cR}\,\frac{I_1(r\beta)}{I_1(R\beta)}, \tag{2}$$

where I — current intensity, R — sample radius, c — constant depending on the choice of units, I_1 — modified Bessel function and $\beta = \omega_0^{1/2}$ describes the mean value of the order parameter. A similar expression was obtained by Kogan [13] but it included the constants characterizing nonlocal properties of the vortex system and its adoption to a certain inhomogeneity which are impossible to obtain experimentally. The plot of the curve (2) for $I = 50$ A, $R = 2\times10^{-3}$ m, $c = 1$, $\beta = 0.018$ (it is equivalent to the reduced field $b = 0.9996$), $\kappa = 4.7$ and $\lambda = 4\times10^{-6}$ m is shown in Fig. 6. It is seen that although the character of the curve is similar to the measured one, quantitative agreement between theory and experiment is not good. It is reasonable because the parameters characterizing our samples are different than the ones appearing in theory.

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