Supercond. Sci. Technol. **13** (2000) 745–748. Printed in the UK PII: S0953-2048(00)11250-3

Field-cooled magnetization measurements of Nd-123 bulk superconductors

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Received 21 January 2000

Abstract. The field-cooled (FC) magnetization M is measured as a function of the applied external field, H_a, for various bulk, Nd-based 123 superconductors which exhibit different magnetization–field characteristics (i.e. with and without secondary peak effect). We find that the FC magnetization data reproduce directly the $M(H_a)$ behaviour measured after zero-field cooling. Based on the critical state model, we derive expressions for the field-cooled magnetization, and show that a large $M(0)$ is essential to achieve large trapped fields in superconducting permanent magnets.

1. Introduction

High magnetic fields can be trapped in bulk type-II superconductors with strong pinning. This leads to the development of quasi-permanent magnets using $YBa_2Cu_3O_{7-\delta}$ (YBCO) and $NdBa_2Cu_3O_{7-\delta}$ (NdBCO) discs [1, 2]. The maximum field, $B_0 = \Delta B(0)$, of the spatial distribution of the trapped field depends on the critical current density, j_c, and on the size of the persistent current loops in the superconductor. As a consequence, it is necessary to grow large monolithic bulks with a high j_c. The critical current density, however, is found to depend strongly on the applied magnetic field. Especially in the NdBCO superconductors, j_c in the high field region is enhanced by the presence of the secondary peak or fishtail effect [3]. Due to this peculiar shape of the $j_c(B)$ curves arises now the question as to which part of the $j_c(B)$ curve is most essential to achieve a large trapped field, B_0.

In the present paper, we investigate the field behaviour of the magnetization, $M(B)$ after field-cooling to and subsequent removal of a given field. This procedure is equivalent to most of the field-trapping experiments employing a scanning Hall probe on large bulks [2, 4, 5]. We find that the $M(B)$ behaviour reproduces exactly the $j_c(B)$ behaviour obtained from standard dc magnetization measurements by means of SQUID magnetometry performed after zero-field cooling of the sample. Further, we compare the $M(B)$ of the small samples employed in SQUID measurements with $\Delta B(B)$-data from trapped field measurements on large bulks. These results are then discussed using model calculations.

2. Samples and experimental methods

Magnetization was measured by means of a commercial SQUID magnetometer [6] in both FC (cooling the sample in a constant field down to a given temperature, and then reducing the field to 0 T in several steps) and ZFC conditions (after zero-field-cooling the field is ramped up to a maximum value and down again). The scan length in the SQUID was restricted to 1 cm in order to avoid field inhomogenities. Small samples of NdBCO and $(Nd_{0.33}Eu_{0.33}Gd_{0.33})Ba_2Cu_3O_y$ (NEG) with typical sizes of $1.5 \times 1.5 \times 0.8$ mm^3 were employed. For trapped field measurements, we used bulks with a diameter of 4 cm and a thickness of 1.5 cm. The field distribution was scanned by a Hall probe at a distance of 5 mm from the face of the superconductor; the apparatus is described in [5]. The description of the sample preparation is given in detail elsewhere (NEG [7, 8], and NdBCO single crystals [9, 10]).

3. Results and discussion

Figure 1 presents the $M(B)$ measurements of an NdBCO single crystal after field-cooling. The curves obtained at $T = 35$ K, 60 K and 77 K were measured after cooling the sample in 7 T, and then reducing the applied field stepwise to zero. At $T = 60$ K, we also measured ‘minor curves’, i.e. the sample is field-cooled in the presence of a certain field (<7 T), which subsequently is reduced. At all temperatures, a well pronounced fishtail shape is observed. The minor curves always begin at $M \approx 0$, corresponding to a fully penetrated state with no flux density gradients (= equilibrium value). Ramping the field down produces large flux density gradients (= large j_c), which lead to the observed $M(B)$

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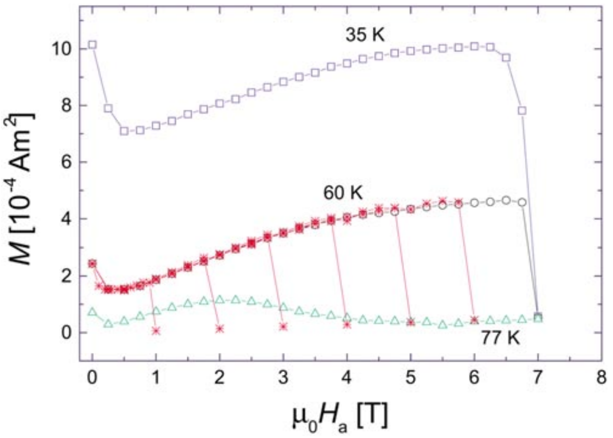

Figure 1. Various FC measurements of m on sample NEG-3a at 35 K, 60 K and 77 K. Minor loops were performed at 60 K, i.e. the sample was field-cooled to 6, 5, 4, 3, 2, 1 T before ramping down the field. The resulting FC magnetization is always close to equilibrium, but ramping down the field builds up the flux density gradients.

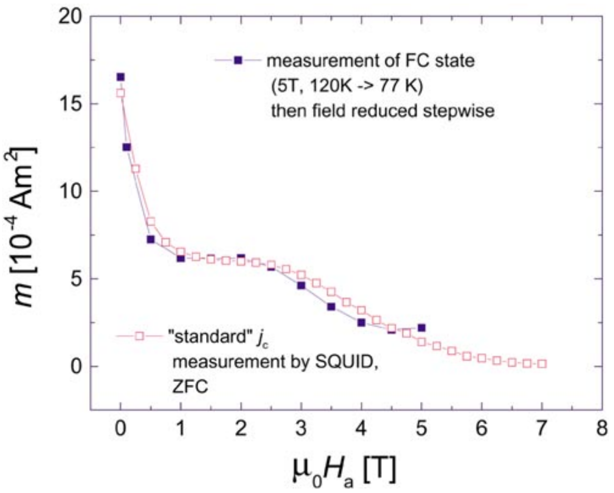

Figure 2. Comparison of the FC magnetization ($T = 77$ K) with the magnetization obtained in a 'standard' j_c measurement where the sample is first zero-field-cooled. The $M(B)$ behaviour is found to be identical. The sample in this figure is an NEG sample with an addition of 50 mol% NEG-211. Furthermore, the fishtail peak is not well pronounced, which is also reproduced in the FC data.

curves. We notice a striking resemblance between the $M(B)$ profile, and the $j_c(B)$ behaviour obtained in ZFC conditions.

In order to verify quantitatively that the $M(B)$ behaviour is related directly to $j_c(B)$, we plot in figure 2 two such measurements on an NEG sample with an addition of 50 mol% NEG-211 particles [8]. This sample exhibits an extremely high $j_c(0)$ value of $\approx 120\,000$ A cm^{-2} at 77 K, self-field. After a background correction (which is essential in the NEG materials due to the large paramagnetic moments of Nd and Gd, see e.g. [11]), the two datasets practically coincide. These measurements indeed show that the very large $j_c(0)$ is also evident in $M(0)$ after FC.

A simple critical-state model analysis can be useful to understand the close relation between the two types of measurement. Consider the process where the applied field is ramped down to zero from the initial frozen-in applied field. Let us limit the discussion to stages where the critical state is established throughout the cylinder, i.e., the magnetization (magnetic moment per unit volume) is given by

$$M = R^{-2} \int_0^R j_c(r) r^2 \,\mathrm{d}r. \qquad (1)$$

A general B-dependence of the critical current is included here by allowing j_c to be a function of position. Writing $j_c(r)$ as a series expansion we obtain

$$\begin{aligned} j_c(r) &= j_c(R) + j_c'(R)(r - R) + \ldots \\ &= j_c(B_a)[1 - \mu_0 j_c'(B_a)(r - R) + \cdots]. \end{aligned} \qquad (2)$$

Inserting this into equation (1) one finds that the magnetization can be expressed as

$$M(B_a) = \tfrac{1}{3} j_c(B_a) R [1 + \tfrac{1}{4}\mu_0 R j_c'(B_a) + \cdots] \qquad (3)$$

where the leading term is the standard result of the Bean model [12].

A similar analysis can be carried out for the width, ΔM, of the MHL measured after ZFC. The result is, following [13]

$$\Delta M(B_a) = \frac{2}{3} j_c(B_a) R \left[1 + \frac{1}{40}\mu_0^2 R^2 \frac{\mathrm{d}^2}{\mathrm{d}B_a^2} j_c^2(B_a) + \cdots \right] \qquad (4)$$

which justifies the usual way to infer $j_c(B)$ from MHLs provided that the correction terms are small. Inserting numbers for R, $j_c'(B)$ and also for the second derivative we find that in the present case the correction terms are small, and one concludes that measurements of $M(B_a)$ in FC and of $\Delta M(B_a)$ in ZFC conditions both correspond to the B-dependence of the critical current.

Figure 3 presents a comparison of the $M(B)$ behaviour (after FC), with a trapped field measurement using a bulk sample of the same batch. The trapped field, ΔB, in the plot is defined as the maximum excess field in the sample, see figure 4. Again, the two datasets yield practically the same field dependence; however, there is a difference in the vicinity of the fishtail peak. The peak effect in the $\Delta B(B_a)$ data is far less pronounced than in the $M(B_a)$ data. This may reflect sample inhomogeneities, as $\Delta B(B)_{\max}$ is not exactly located in the sample centre.

The excess field ΔB trapped in the centre of a cylinder can be expanded in a series similar to the magnetization. From equation (2), and using that $\mu_0 j_c(r) = -\mathrm{d}B/\mathrm{d}r$, it follows that

$$-\int_{B_a+\Delta B}^{B_a} \mathrm{d}B = \mu_0 j_c(B_a) \int_0^R [1 - \mu_0 j_c'(B_a)(r - R) + \cdots]\,\mathrm{d}r \qquad (5)$$

which gives

$$\Delta B(B_a) = \mu_0 R j_c(B_a)[1 + \tfrac{1}{2}\mu_0 R j_c'(B_a) + \cdots]. \qquad (6)$$

Here, it should be noted that the surface field is at most only 50% of the calculated value because on the surface more than half of the full cylinder is missing in the comparison with the calculated situation.

The calculations show that $\Delta B(0)$ is determined mainly by $j_c(0)$. In the case of a large sample (i.e. large radius), the

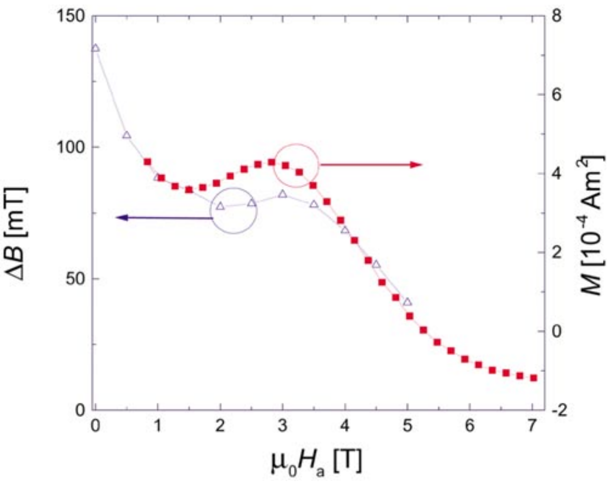

Figure 3. Comparison of trapped field data ΔB of a bulk sample with the $j_c(B)$ behaviour measured by means of a SQUID magnetometer.

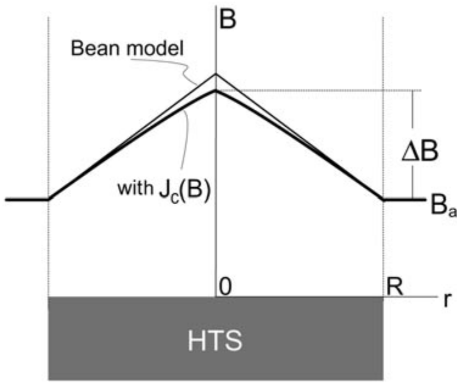

Figure 4. Schematical drawing of the critical state model with a field-dependent critical current density. The trapped field, ΔB, is defined as the maximum excess field in the sample.

correction term in equations (3), (4) and (6) becomes more pronounced. One should, however, bear in mind that a typical disc used for the trapped field measurements (diameter 4–10 cm, $d = 1$–2 cm) has a quite large demagnetization factor, so that the Bean model in the consideration for the parallel geometry is not generally applicable. The resulting flux density profiles start to resemble the typical shape of 'thin' superconductors [14–16].

Another important issue is the relevance of the fishtail effect, which is present in practically all Nd-based superconductors of the 123 type [17]. Using an extension of the critical state model as presented in [18], we can calculate flux density profiles of a cylindrical sample exhibiting the fishtail effect. In this case, the resulting flux density profiles are not straight, but curve inwards. This curvature is, however, very similar to the situation of a large demagnetization factor. The field dependence of j_c in the thin geometry does not have such a large effect as for long cylinders [16]. Therefore, for typical superconducting discs the most important factor in achieving a large trapped field in superconducting bulks, besides the requirement that the currents have to flow in a large mono-domain, is the zero-field current density, $j_c(0)$. Further support for this conclusion comes from the present record values of trapped fields which are achieved in irradiated samples (see e.g. Ren *et al* [1]). Such irradiation procedures are known to increase $j_c(0)$ considerably, and the peak effect nearly vanishes. Here, we also should point out that the $M(B)$ data obtained in FC conditions allow measurement of the $j_c(B)$ dependence, even in a case when the sample cannot otherwise be fully penetrated by flux. Also, it should be noted that the field-cooling with subsequent ramping down the field to 0 T produces the same flux density gradients ($= j_c$) as under ZFC conditions. However, if one energizes a super-permanent magnet in FC conditions, the resulting stresses on the material are smaller, as discussed in [19].

4. Conclusions

Measurements of the magnetization $M(B)$ after field-cooling are found to give similar values to measurements performed under zero-field-cooling conditions, which is supported by the results of model calculations. Furthermore, the most important factor in achieving high trapped magnetic fields in bulk superconductors besides the large mono-domain areas is the current density in zero field. The high current density due to the fishtail effect gives only a correction factor, which becomes more important if the radius of the superconducting disc is large.

Acknowledgments

We would like to thank T Miyamoto for performing the trapped field measurements and M Muralidhar, T Higuchi and Th Wolf for the samples used in this study. This work is partially supported by the Research Council of Norway and NEDO.

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