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A new fast and non-destructive method for evaluating the superconducting properties of bulk materials

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ABSTRACT: This paper aims at reporting a new, simple and low-cost experimental technique designed for investigating the electrical properties of disk-shaped superconducting samples. The principle is similar to that of an induction motor. Two neighbouring and 90° out-of-phase AC magnetic fields are applied perpendicularly to the disk to be measured. As a result, the material experiences an electromagnetic torque which depends on its electrical properties. In this paper the experimental system is briefly described and illustrative measurements on different HTS are reported and discussed.

1. INTRODUCTION

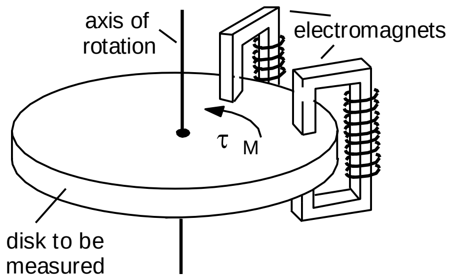
Nowadays, materials fabricated in bulk form can be used for a wide range of engineering applications including magnetic bearings and flywheels (Campbell et al 1997). Investigating the electrical properties of these specimens as a whole requires non-destructive methods applicable to large disks (diameter > 2 cm), which excludes the traditional characterization techniques appropriate for small samples. In the case of melt-textured (RE)BCO materials, two methods are commonly used (i) measuring the levitation force exerted on a permanent magnet placed above the sample (Murakami 1992), or (ii) scanning a miniature Hall probe over the top surface of the disk (see e.g. Zhang et al 1997).

In this paper we report results obtained with a fast and inexpensive method for evaluating the superconducting properties of large disks. The aim is to have a quick estimation of the superconducting character of the material. In this way, poor quality samples can be either rejected or improved, whereas specimens which exhibit good electrical properties can be selected for further studies such as their electrical resistivity and magnetic susceptibility. The principle of the technique is described in the next section. Then, measurements made on high-T_c superconductors are presented and compared to R(T) curves.

2. EXPERIMENT

2.1 Principle of operation

The principle of operation is based on that of an induction motor. The device, illustrated in Fig. 1, is similar to home electricity counters, except that the aluminium disk usually used in such counters is replaced here by the material to be measured. The disk, able to spin freely around a vertical axis, is engaged in the air-gap of two neighbouring electromagnets. These magnets are fed with 90° out-of-phase currents and generate magnetic fields which are both applied perpendicularly to the disk. This causes the sample to experience an electromagnetic torque τ_M which is related to the



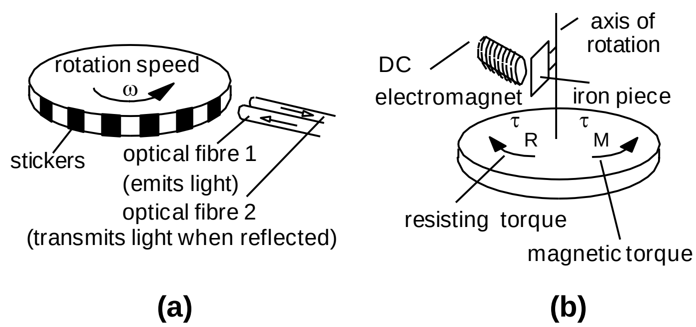


Fig. 1 : Schematic diagram of the experimental system

Fig. 2 : Schematic illustration showing the principle of (a) rotation speed and (b) torque measurements

electrical behaviour of the material. More precisely, if the disk is a normal conductor (e.g. aluminium) characterized by a given resistivity ρ , analytical expressions (Listray 1970) show that the torque is, in a first approximation, inversely proportional to ρ . For conductors with very low resistivity, the torque is thus expected to be quite large.

However, in the case of a superconducting material ($\rho = 0$), this result cannot be generalized. The reason is that the interaction between the disk and the applied magnetic field cannot be described by a linear E-J relationship, as is the case for a normal conductor. Moreover, the flux penetration is intractable to treat analytically because of (i) the flat geometry of the sample (demagnetization effects),
(ii) the non-uniformity of the applied magnetic fields and (iii) the granular microstructure of HTS, which gives rise to inter- and intra-granular currents. In spite of these difficulties, one can fairly assume that the shielding current paths generating the torque are only efficient below T_c, in which case they are limited at their maximum value (J_c). Therefore this kind of measurement performed on a superconducting sample should give an indirect picture of its critical temperature and critical current density.

2.2 Experimental details

In order to reach cryogenic temperatures, the whole system depicted in Fig. 1 is simply immersed in liquid nitrogen (T = 77 K) and then allowed to warm up slowly during liquid nitrogen evaporation. In practice, the disk-shaped sample is placed in a plexiglass box which several holes have been drilled in. This ensures a good thermal contact between the material and the nitrogen.

The material's response can be probed by measuring either the rotation speed of the disk or the electromagnetic torque itself. The rotation speed is measured optically. A series of alternatively black and white stickers is placed on the periphery of the box, as depicted in Fig. 2a. Two adjacent optical fibres are used. The first fibre emits light which is either reflected or absorbed by the stickers. The luminous signal is then transmitted by the second fibre to a phototransistor inserted in an appropriate electronic circuit. The frequency of the output signal, directly proportional to the rotation speed, is then measured using a HP 34401A multimeter. In order to measure the torque, an iron piece has been bound up with the rotating system (Fig. 2b). This piece is attracted by an electromagnet fed with DC current; this generates a resisting torque. The value of the magnet DC current is then adjusted such that the system is immobile. At this moment both electromagnetic and resisting torques have the same value.

3. RESULTS AND DISCUSSION

In view of testing the apparatus, two kinds of HTS materials have been investigated: a polycrystalline $Bi_2Sr_2Ca_2Cu_3O_{10}$ ceramic (Bi-2223) and a melt-textured $DyBa_2Cu_3O_7$ monolith (Dy-123). The corresponding synthesis processes are detailed elsewhere (Vanderbemden et al 1998, Cloots et al 1996). After being measured by the system described above, the disks have been cut and characterized by their electrical resistivity. Results (Fig. 3) show that the R(T) curve for the Bi-2223

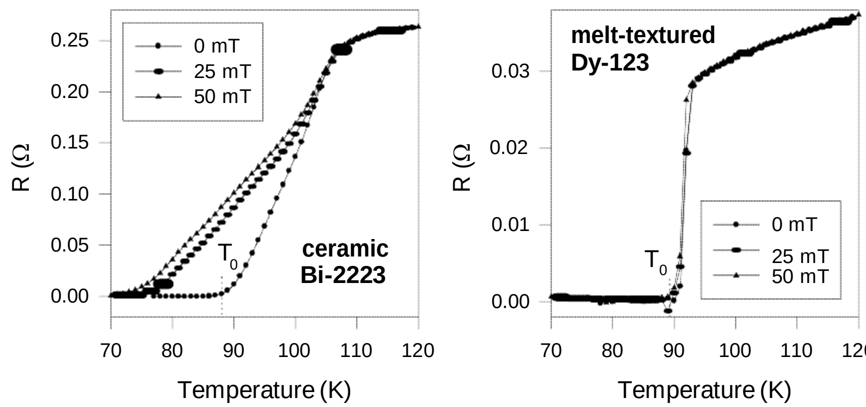


Fig. 3 : Resistance measurements for the Bi-2223 ceramic and the Dy-123 textured samples

material displays the typical "resistive foot" structure usually observed in low-J_c ceramics. On the other hand, the resistance transition measured within a large grain extracted from the melt-textured Dy-123 material is quite narrow and not significantly influenced by the small magnetic fields used, which suggests a much higher J_c. In addition, an aluminium disk property has been measured in order to bring out the qualitative difference in behaviour between conducting and superconducting materials.

Figure 4 compares the rotation speed of three disk-shaped samples (Al, Bi-2223, Dy-123) having approximately the same dimensions (diameter ≈ 20 mm, thickness ≈ 2 mm). Since the temperature of a rotating sample cannot be easily measured, the speed is simply expressed as a function of the liquid nitrogen level *h*.

The results shown in Fig. 4 can be explained considering that the rotation speed ω is mainly limited by the friction force between the disk and the liquid. When the disk is completely immersed (*h* > 35 mm), ω is nearly independent of *h* because the friction force is almost a constant. During the liquid nitrogen evaporation (decreasing *h*), the surface of the disk in contact with the liquid becomes smaller and ω slowly increases. When the liquid nitrogen just brushes against the bottom of the disk (*h* ≈ 30 mm), the box containing the sample floats over the liquid, which results in a drastic increase of the rotation speed. At this level, the disk temperature is still close to 77 K. On lowering the level further, the sample warms up and the rotation speed decreases. Notice the difference between the normal conductor - for which the small reduction of ω is due to the positive (dρ /dT) - and the superconductors - for which ω significantly decreases and vanishes when the liquid N_2 level is sufficiently low, i.e. once the sample temperature exceeds T_c.

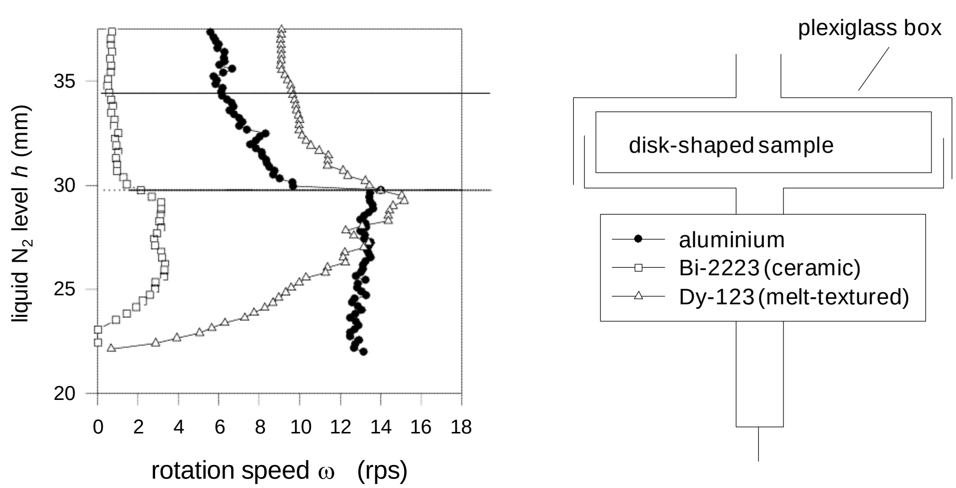


Fig. 4 : Relation between the rotation speed and the liquid nitrogen level

In order to get a fair comparison of superconducting samples, one should preferably work in a regime for which the rotation speed is insensitive to the nitrogen level. This only happens when the disk is completely immersed. In such a case, according to Fig. 4, the rotation speed of the Bi-2223 ceramic is much smaller than that of the Dy-123 material. This result is consistent with the R(T) curves (Fig. 3) pointing out the strong influence of weak-links on the superconducting properties for the Bi-2223 specimen.

Another interesting parameter which can be deduced from the data reported in Fig. 4 is the level at which ω goes to zero. This level is seen to be nearly the same for both materials. From Fig. 3,
the "zero-resistivity" temperatures T_0 - corresponding to the establishment of a bulk *inter*granular percolation path - are very close to each other indeed, in spite of much different *intra*granular T_c's. This underlines the agreement found between the rotation speed measurements and the R(T) curves.

Finally, the electromagnetic torque has been measured using the experimental set-up shown in Fig. 2b. In this experiment, the system is immobile and the sample temperature has been measured by a copper/constantan (type T) thermocouple. Results are shown in Table 1.

	Al	**Bi-2223**	**Dy-123**
torque (77 K)	10.3	3.9	15.2
torque (85 K)	9.9	1.7	6.7

Table 1 : Electromagnetic torque (expressed in arbitrary units)

As can be seen, the torque of the superconducting samples significantly decreases with increasing temperature, whereas the torque measured on the aluminium disk is almost a constant. These results nicely corroborate the rotation speed measurements discussed above.

Although some numerical simulations could be beneficial in understanding the exact relationship between the measured signal (rotation speed or torque) and the physical properties of the material, the system described in this paper appears to be sensitive to the critical current density as well as to the critical temperature of the studied samples.

4. CONCLUSION

A new experimental set-up has been used in order to evaluate the properties of superconducting disks. The key advantage resides in the possibility of studying large pellets without cutting them. Both speed and torque measurements have been shown to be consistent with resistance measurements. The apparatus described here is less accurate than conventional susceptometers or magnetometers but represents nevertheless a fast and interesting way of estimating the quality of disk-shaped superconductors.

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