Measurements of Thermal Effects in a Bulk YBCO Single Domain Superconductor Submitted to a Variable Magnetic Field

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***Abstract*—When YBCO single domains are subjected to a variable magnetic field, the motion of vortices may give rise to a significant temperature increase and a degradation of the superconducting properties. We have experimentally investigated such effects in bulk melt-processed YBCO single domains. Several temperature sensors, a pick-up coil and two Hall probes were placed against the surface of a monolithic bulk YBCO pellet. Data were simultaneously recorded during the application of ac magnetic fields of various amplitudes, either with or without a pre-existing dc trapped flux. The measurement results agree well with to those obtained by numerical modeling. It was also found that a superimposed dc magnetic moment reduces the temperature increase caused by the ac magnetic field.**

***Index Terms*—High-temperature superconductors, magnetic variables measurement, thermal variables measurement.**

I. INTRODUCTION

BULK melt-processed $YBa_2Cu_3O_7$ (YBCO) single domains have been shown to trap significant magnetic inductions at liquid nitrogen temperature [1]–[3]. These materials are extremely promising as a competing technology for permanent magnets in several engineering applications including magnetic bearings and brushless ac machines [4]–[7]. In many topologies envisaged for designing an efficient electrical motor based on bulk superconductors, the YBCO sample is permanently magnetized parallel to its c-axis and placed in the machine rotor [8], [9]. In this configuration, the sample is likely to experience transient variations of the applied magnetic field caused by modifications of the applied torque on the shaft. In a similar way, when bulk superconductors are used in magnetic bearings, the vibration or the irregular magnetization of the permanent magnet can result in a time-varying magnetic induction [4]. The resulting vortex motion may cause large hysteresis losses and a significant temperature increase which, in turn, has a detrimental effect on the initial trapped flux [10], [11].

The problem of accurately predicting the temperature rise within bulk superconductors subjected to variable magnetic fields is quite intricate because of the complex interplay between the physical parameters involved: on the one hand, the temperature distribution is controlled by the power P dissipated at each point of the sample; on the other hand, P is a function of both the magnetic induction B and the critical current density J_c which is strongly temperature dependent. In practice, a detailed understanding of these effects requires specific experimental investigations. Fujishiro *et al.* successfully measured the temperature rise and the field distribution during pulse field magnetizing of bulk superconductors [12], [13]. Tsukamoto *et al.* have calculated and measured the temperature distribution at the surface of a permanently magnetized bulk superconductor *after* the application of an external ac magnetic field [14]. In a previous work [15], we measured the temperature distribution *during* the application of the ac magnetic field and compared the measurement result to theoretical predictions.

The aim of the present paper is to complement the experimental investigations described above by carrying out simultaneous measurements of temperature and magnetic induction distribution on a bulk melt-processed single domain during the application of an ac magnetic field. We also wish to investigate the influence of a pre-existing trapped flux on the thermal effects taking place in these materials.

II. EXPERIMENT

Bulk melt-processed YBCO single domains were prepared by a top seeding technique. The details of the synthesis process as well as microstructural characterizations of the materials have been described in previous papers [16], [17].

The disk-shaped samples have a typical size of 10 mm diameter and 8 mm thickness. The superconducting properties were determined by conventional measurement techniques [18]. The material is characterized by a critical temperature T_c ca. 91 K and critical current density J_c ca. $10^4\ \mathrm{A/cm^2}$ at $T = 77$ K and $B = 0.3$ T.

A bulk YBCO cylindrical pellet was mounted with the following sensors, as schematically shown on Fig. 1: (i) several E

Manuscript received August 26, 2006. This work was supported by the Belgian National Fund for Scientific Research (FNRS) and the University of Liège (Belgium). The work of Ph. Vanderbemden was supported by the FNRS under a travel grant. The work of S. Meslin was supported by the Ministère Français de la Recherche et de la Technologie under a Ph.D. fellowship.

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Digital Object Identifier 10.1109/TASC.2007.898988

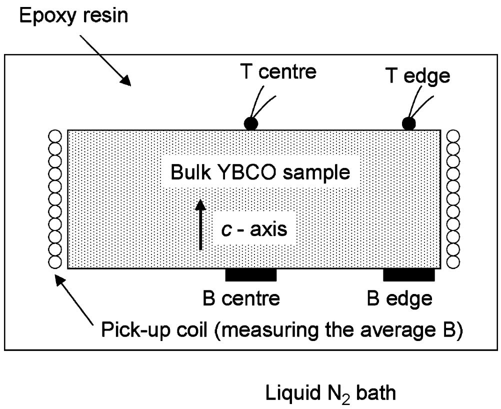

Fig. 1. Schematic diagram of the sample side view, showing the location of two of the temperature sensors (centre + edge), the two Hall sensors (centre + edge) and the pick-up coil.

type thermocouples attached to the top surface and located at several distances from the center, (ii) two AREPOC Hall probes (active surface 2 mm × 3 mm) placed against the sample bottom surface and (iii) a pick-up coil closely wound around the lateral surface [19]. The two Hall sensors probe the c-axis local magnetic induction respectively at the centre and at 1.5 mm from the sample edge. In order to limit Joule heating, both sensors were fed with the smallest possible current $(\mathrm{I} \sim 1\ \mathrm{mA})$ allowing an acceptable sensitivity. The pick-up coil measured the c-axis magnetic induction averaged over the whole single domain. The sample and the sensors were embedded in epoxy resin $(\mathrm{thickness} = 5\ \mathrm{mm})$ and immersed in liquid nitrogen $(T = 77\ \mathrm{K})$. The sample was then submitted to an ac magnetic field ($f = 50$ Hz, $H \| c$-axis) generated by a copper coil. A second coaxial coil of larger diameter was also used to superimpose a dc magnetic field parallel to the ac field. The magnet current and all sensor signals were simultaneously recorded using a PCI-6221 National Instruments multi-channel data acquisition card.

In addition, the temperature dependence of the thermal conductivity $\kappa(T)$ of small bar-shaped samples was measured using a home-made experimental set-up inserted in a Quantum Design Physical Property Measurement System (PPMS) [20], [21].

III. Results and Discussion

A. Simultaneous Thermal and Magnetic Measurements

Fig. 2 compares the time-dependence of the temperature and the magnetic properties of such a bulk YBCO single domain using the experimental set-up described above. The sample is initially cooled down to $T = 77$ K in zero-field. At $t = 0$ an ac magnetic field (62 mT, 50 Hz) is applied.

We first focus on the temperature measured at the centre and at the sample edge (Fig. 2(a)). For $t < 300$ s, both temperatures are found to increase in a sublinear manner. Next, thermal runaway occurs $(t \approx 320\ \mathrm{s})$ and both temperatures eventually exhibit a steady-state regime after approximately t ≈ 330 s. As can be seen in the inset of Fig. 2(a), the initial edge temperature is higher than the temperature measured at the sample centre whereas the opposite behavior is observed for $t > 50$ s. When

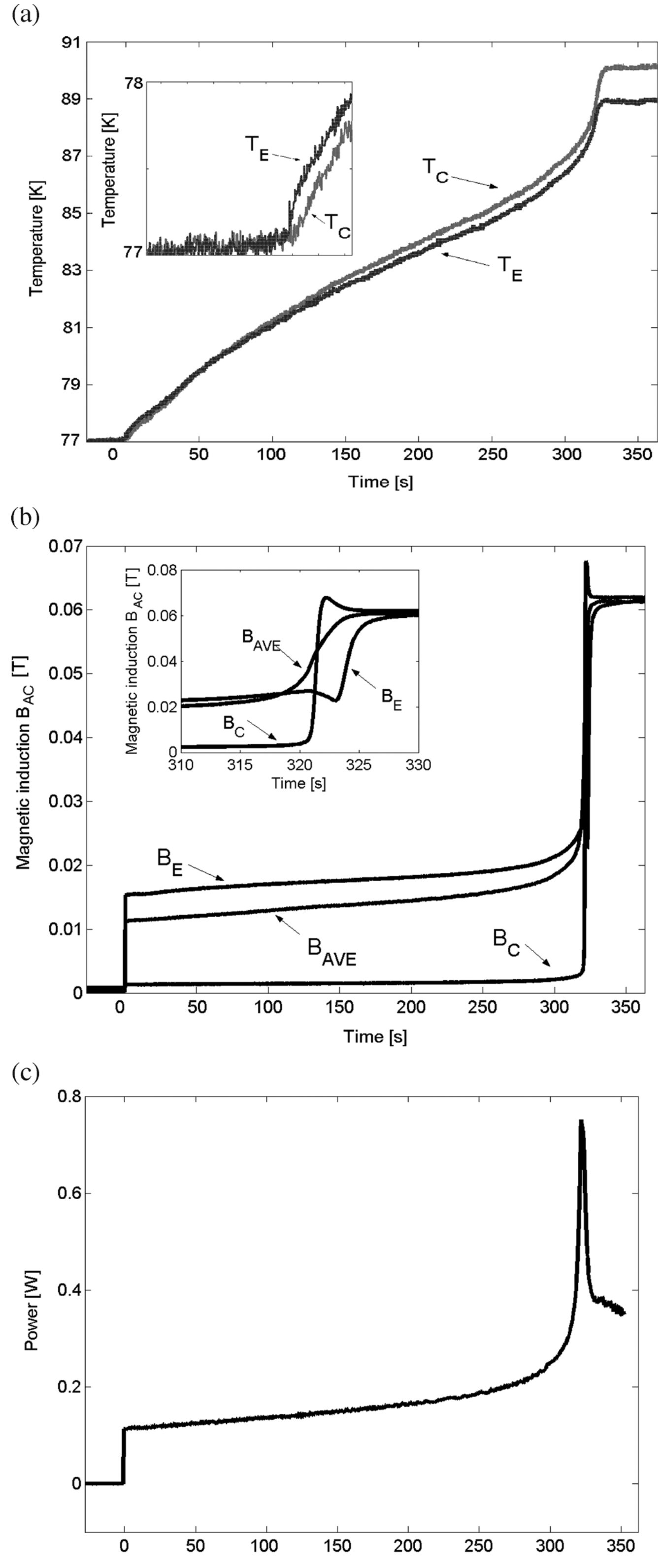

Fig. 2. Simultaneous measurements on a YBCO single domain subjected to an ac magnetic field (62 mT–50 Hz) applied at $t = 0$. (a) Temperature measured at the centre (T_C) and at the edge (T_E) of the top surface. Inset: initial temperature increase. (b) Local ac magnetic induction probed by Hall probes at the centre (B_C) and at the edge (B_E), average magnetic induction probed by the sensing coil (B_{ave}). (c) Average dissipated power.

the steady-state is reached, the temperature of the central thermocouple is ca. 1.2 K higher than the temperature of the edge.

This result underlines that the cooling in the periphery is more efficient than in the centre.

Second, we turn to the behavior of the magnetic flux lines during the same experiment. Fig. 2(b) compares the *local* ac magnetic induction at the sample edge (B_{E}), at the sample centre (B_{C}) and the *average* ac magnetic induction B_{ave} probed by the pick-up coil. As long as $t < 315$ s, the three signals are much smaller than the applied induction $\mu_0 H = 62$ mT and satisfy $B_{\mathrm{C}} < B_{\mathrm{ave}} < B_{\mathrm{E}}$. This result is expected because of the efficient magnetic shielding occurring while the whole sample is still in the superconducting state ($T < 90$ K). The slight increase of the measured magnetic inductions during this time interval can be attributed to the decrease of the critical current density J_{C} caused by the sample warming (cf. Fig. 2(a)). Before the sample is completely penetrated by the flux, the local magnetic inductions are found to display a remarkable and reproducible non-monotonic behavior (inset of Fig. 2(b)): the *central* induction displays an abrupt jump,—transiently exceeding the applied induction—, whereas the *edge* induction exhibits a minimum preceding the final rise. Such results clearly suggest a migration of flux lines from the sample edge towards the centre when the core temperature increases. This flux migration transiently reduces the local magnetic induction B_E at the outer perimeter of the sample, whence resulting in the observed minimum. Such a behavior is in agreement with the temperature distribution plotted in Fig. 2(a), showing approximately a 1 K temperature gradient between the central part and the edge of the sample.

Third, continuous recording of the $B(t)$ and $H(t)$ signals throughout the experiment allowed us to calculate the dissipated power P over the whole sample volume for each cycle of the ac field. The result, plotted in Fig. 2(c), displays a sharp peak (∼0.7 W) that coincides with the thermal runaway and the abrupt rise of the magnetic inductions (Fig. 2(b)).

Interestingly, the dissipated power does not vanish once the steady-state is reached ($t > 330$ s) but remains to some non-zero value (∼0.35 W). These results clearly suggest that some parts of the sample are still in the superconducting state in this regime, although the average magnetic induction is close to the applied induction. The heat flux generated by ac losses is constantly drained out by thermal conduction through the epoxy resin layer, resulting in time-independent measured temperatures.

The set of measurements described above was repeated in the presence of several dc magnetic fields superimposed to the ac field. The results are qualitatively similar to those depicted in Fig. 2, but the time intervals before the steady state regime increase with increasing dc field (see Table I). The experiment was also carried out in the presence of a permanent trapped flux before applying the ac magnetic field. This configuration yields the same phenomenon: the presence of a small dc magnetic moment reduces the temperature increase caused by the ac field or, conversely, increases the time required to reach a constant temperature. Although the exact reason for this behavior remains unclear, it may be linked to the field-dependence of the critical current density $J_c(B)$: the dc magnetic moment globally reduces the average J_c and the dissipated power throughout the experiment.

TABLE I
TIME BETWEEN THE START OF THE AC SOLICITATION AND THE STEADY-STATE REGIME (CONSTANT TEMPERATURE)

superimposed dc field $\mu_0 H_{DC}$	Time interval Δt
0 mT	Δt_0 (~ 325 s)
28 mT	1.10 Δt_0
55 mT	1.26 Δt_0
Magnetized sample	1.08 Δt_0

Time interval needed to reach the steady-state regime when an ac magnetic field (62 mT–50 Hz) is applied at $t = 0$. The term 'magnetized sample' refers to a sample in which magnetic flux was trapped (Field Cooling [FC] procedure down to $T = 77$ K under 0.5 T) before starting the ac sollicitation.

TABLE II
PARAMETERS USED FOR THERMAL MODELING

Parameter	Value
YBCO thermal conductivity ‖ *ab*	7.5 W / m K
YBCO thermal conductivity ‖ *c*	2 W / m K
YBCO thermal diffusivity ‖ *ab*	10^{-5} m²/s
Epoxy thermal conductivity (isotropic)	0.055 W / m K
Epoxy thermal diffusivity (isotropic)	4.4 10^{-7} m²/s

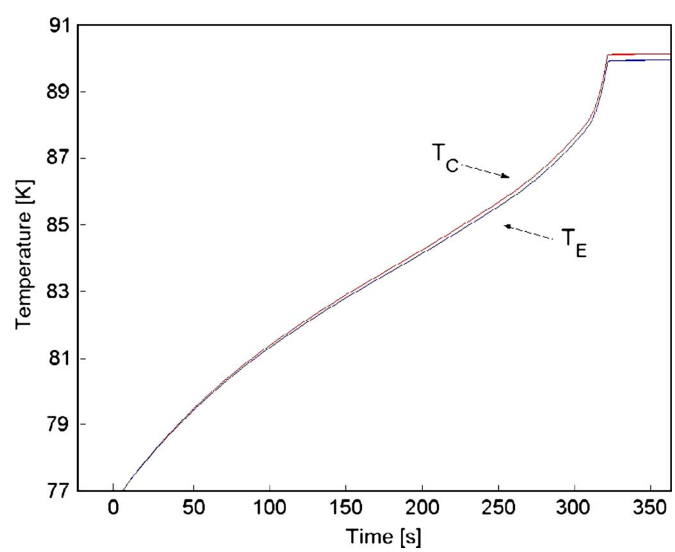

Fig. 3. Computer modeling of the temperature at the locations where thermocouples are attached to the sample surface.

B. Computer Modeling Results

The results displayed in Fig. 2 can be used for checking the validity of the parameters used in computer modeling. Thanks to the accurate determination of the average power dissipated within the sample (Fig. 2(c)), we can solve the heat equation using a Finite Difference Method and compute the temperatures at the locations where thermocouples are attached to the top surface (cf. Fig. 1). The thermal parameters of the superconductor were deduced from measurements carried out on small samples extracted from the single domain, whereas those of the insulating layer were taken from the literature [22]. All are summarized in Table II. Agreement between modeling (Fig. 3) and experimental data (Fig. 2(a)) is very satisfactory, although our modeling assumes that the dissipated power is uniform within the sample.

IV. Conclusion

Thermal effects resulting from the application of an ac magnetic field to a large bulk melt-textured YBCO single domain were measured using different sensors. The results so obtained allow the average dissipated power to be determined; they point out to the very inhomogeneous temperature and flux distribution within the sample. It has also been found that the presence of a dc magnetic moment substantially reduces the temperature increase caused by the ac field. Modeling the temperature evolution can be satisfactorily done.

Acknowledgment

The authors would like to thank J. Lecourt for the samples forming, and J.-F. Fagnard and F. Wolff-Fabris for their assistance in carrying out the measurements.

References

[1] G. Fuchs, G. Krabbes, K.-H. Müller, P. Verges, L. Schultz, R. Gonzalez-Arrabal, M. Eisterer, and H. W. Weber, "High magnetic fields in superconducting permanent magnets," *J. Low Temp. Phys.*, vol. 133, pp. 159–180, 2003.

[2] J. R. Hull and M. Murakami, "Applications of bulk high temperature superconductors," *Proceedings of the IEEE, Applications of Superconductivity*, vol. 92, pp. 1705–1717, 2004.

[3] M. Sander, "Finite element design and magnetization issues of ring-shaped cryo-permanent magnets," *IEEE Trans. Appl. Supercond.*, vol. 16, pp. 1158–1561, 2006.

[4] K. Matsunga, N. Yamachi, M. Tomita, M. Murakami, and N. Koshizuka, "Characterization of YBCO bulk superconductors for 100 kWh flywheel," *Physica C*, vol. 392–396, pp. 723–728, 2003.

[5] A. Sato, H. Ueda, M. Tsuda, and A. Ishiyama, "Operational characteristics of linear synchronous actuator with field-cooled HTS bulk secondary," *IEEE Trans. Appl. Supercond.*, vol. 15, pp. 2234–2237, 2005.

[6] M. Miki *et al.*, "Development of a synchronous motor with Gd-Ba-Cu-O bulk superconductors as pole-field magnets for propulsion system," *Supercond. Sci. Technol.*, vol. 19, pp. S494–S499, 2006.

[7] A. M. Campbell and D. A. Cardwell, "Bulk high temperature superconductors for magnet applications," *Cryogenics*, vol. 37, pp. 567–575, 1997.

[8] M. D. McCulloch and D. Dew-Hughes, "Brushless ac machines with high temperature superconducting rotors," *Mat. Sci. Engineering B*, vol. 53, pp. 211–215, 1998.

[9] B. Oswald, K.-J. Best, M. Setzer, M. Soll, W. Gawalek, A. Gutt, L. Kovalev, G. Krabbes, L. Fisher, and H. C. Freyhardt, "Reluctance motors with bulk HTS material," *Supercond. Sci. Technol.*, vol. 18, pp. S24–S29, 2005.

[10] T. Ohyama, H. Shimizu, M. Tsuda, and A. Ishiyama, "Trapped field characteristics of Y-Ba-Cu-O bulk in time-varying external magnetic field," *IEEE Trans. Appl. Supercond.*, vol. 11, pp. 1988–1991, 2001.

[11] P. Laurent *et al.*, "Study by Hall probe mapping of the trapped flux modification produced by local heating in YBCO HTS bulks for different surface/volume ratios," *Supercond. Sci. Technol.*, vol. 18, pp. 1047–1053, 2005.

[12] H. Fujishiro, K. Yokogama, M. Kaneyama, T. Oka, and K. Noto, "Estimation of generated heat in pulse field magnetizing for SmBaCuO bulk superconductor," *Physica C*, vol. 414–414, pp. 646–650, 2004.

[13] H. Fujishiro, S. Kawaguchi, M. Kaneyama, A. Fujiwara, T. Tateiwa, and T. Oka, "Heat propagation analysis in HTSC bulks during pulse field magnetization," *Supercond. Sci. Technol.*, vol. 19, pp. S540–S544, 2006.

[14] O. Tsukamoto, K. Yamagashi, J. Ogawa, M. Murakami, and M. Tomita, "Mechanism of decay of trapped magnetic field in HTS bulk caused by application of AC magnetic field," *J. Mat. Process. Technol.*, vol. 161, pp. 52–57, 2005.

[15] P. Laurent *et al.*, "Study of thermal effects in bulk RE-BCO superconductors submitted to a variable magnetic field," *Journal of Physics: Conference Series*, vol. 43, pp. 505–508, 2006.

[16] J.-P. Mathieu, I. G. Kano, T. Koutzarova, A. Rulmont, P. Vanderbemden, D. Dew-Hughes, M. Ausloos, and R. Cloots, "The contribution of 211 particles to the mechanical reinforcement mechanism of 123 superconducting single domains," *Supercond. Sci. Technol.*, vol. 17, pp. 169–174, 2004.

[17] J. G. Noudem, S. Meslin, C. Harnois, D. Chateigner, and X. Chaud, "Melt textured $YBa_2Cu_3O_y$ bulks with artificially patterned holes: A new way of processing c-axis fault current limiter meanders," *Supercond. Sci. Technol.*, vol. 17, pp. 931–936, 2004.

[18] P. Vanderbemden, A. D. Bradley, R. A. Doyle, W. Lo, D. M. Astill, D. A. Cardwell, and A. M. Campbell, "Superconducting properties of natural and artificial grain boundaries in bulk melt-textured YBCO," *Physica C*, vol. 302, pp. 257–270, 1998.

[19] P. Vanderbemden, S. Dorbolo, N. Hari-Babu, A. Ntatsis, D. A. Cardwell, and A. M. Campbell, "Behavior of bulk melt-textured YBCO single domains subjected to crossed magnetic fields," *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 3746–3749, 2003.

[20] M. Pekala, J. Mucha, P. Vanderbemden, R. Cloots, and M. Ausloos, "Magneto-transport characterization of Dy-123 monodomain superconductors," *Applied Physics A*, vol. 81, pp. 1001–1007, 2005.

[21] J. Mucha, S. Dorbolo, H. Bougrine, K. Durczewski, and M. Ausloos, "Analysis of experimental conditions for simultaneous measurements of transport and magnetotransport coefficients of high temperature superconductors," *Cryogenics*, vol. 44, pp. 145–149, 2004.

[22] [Online]. Available: http://www.yutopian.com/Yuan/prop/index.html