J Supercond Nov Magn (2011) 24: 261–264
DOI 10.1007/s10948-010-1010-7

ORIGINAL PAPER

# Low Field AC Susceptibility Study of YBCO Prepared by Top Seeded Melt Growth

**N. Güçlü · C.M. Yeşilkanat · H. Ağıl · F. Doğan · A. Gencer · U. Kölemen**

Received: 8 September 2010 / Accepted: 16 September 2010 / Published online: 16 October 2010


**Abstract** Superconducting bulk $YBa_2Cu_3O_{7-x}$ (YBCO) material prepared by the melt growth method was characterized by AC susceptibility measurements. The measured susceptibilities were affected by the ac field amplitudes. The measured fundamental susceptibility was compared with the Bean model. An empirical function for the penetration field $H_p = H_\alpha(1-t)^\beta$, where $t$ is the reduced temperature, was obtained. Ac losses were determined at fixed temperatures and compared with theoretical calculations. A qualitative agreement was found between the experimental results and theoretical calculations.

**Keywords** YBCO · AC susceptibility · AC losses · Bean model

## 1 Introduction

From the early days of high $T_C$ superconductivity, ac susceptibility technique has been employed as a probe to study the weak link intergranular region in the high $T_C$ oxide superconductors. General features of the complex ac susceptibility, ($\chi_n = \chi_n' + i\chi_n''$, $n$ being an integer) in these materials are described in [1]. The complex ac susceptibility can give in formation about magnetic properties and the critical-current density $J_c(H)$ concerning the weak link in tergranular region in the high $T_C$ systems. To analyze the temperature and ac field amplitude dependent variation of the ac susceptibility and to estimate critical-current density, the critical state models have been developed. The first physical interpretation came from the original Bean critical state model [2]. In this model, only the odd-order ac susceptibilities are generated because of the critical current density, $J_c$, assumed to be independent of local magnetic field, causing the symmetric $M$–$H$ curves. Later, Kim–Anderson model takes account of local magnetic field $J_c$ and predicts that the even-order ac susceptibilities are also measurable [3]. Chen and Goldfarb used a parameter $p = (2ka)^{1/2}/H_0$ for a long orthorhombic sample [4]. They have showed that for lower values of $p$ the Kim–Anderson model approximately reduces the Bean model and for larger values of $p$ it assumes a field dependence with $H_0 = 0$. This extreme case of the model is called the simplified Kim model [5].

In this paper, the superconducting bulk YBCO was characterized by AC susceptibility measurement. To make comparison between measurements and calculations, we have obtained the temperature dependence for the penetration field $H_p(T)$ from the experimental data. In addition, AC losses were calculated at fixed temperatures and compared with experimental results.

## 2 Experiments

YBCO single crystals were prepared by the top-seeded melt growth technique and described in detail elsewhere [6]. The

N. Güçlü (✉) · U. Kölemen
Department of Physics, Gaziosmanpaşa University, 60240, Tokat, Turkey
e-mail: guclu06@hotmail.com

C.M. Yeşilkanat
Department of Physics, Artvin Çoruh University, 08000, Artvin, Turkey

H. Ağıl · A. Gencer
Department of Physics, Ankara University, 06100, Ankara, Turkey

F. Doğan
Department of Materials Sciences and Engineering, Missouri University of Science and Technology, 65906, Rolla, MO, USA

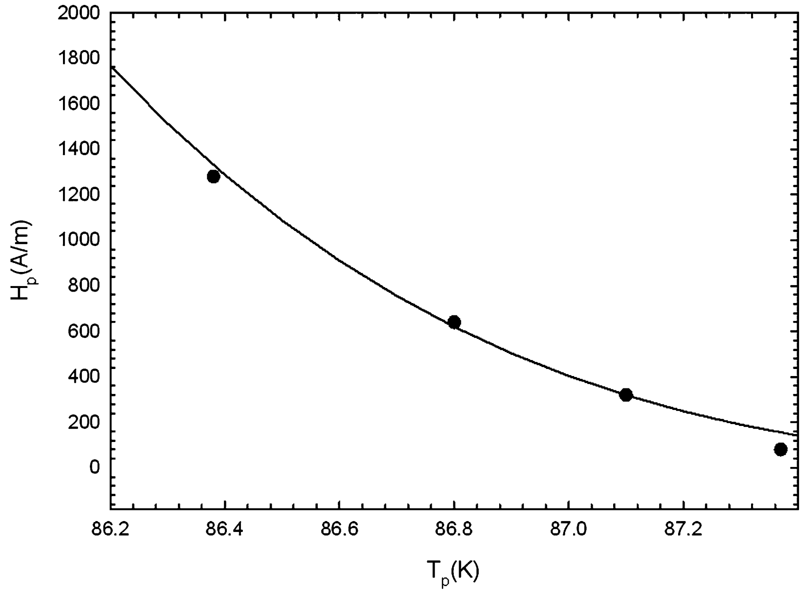



**Fig. 1** The full penetration field, $H_p$, versus the peak temperature, $T_p$

harmonic susceptibility measurements were carried out by a commercial Lake Share 7130-model ac susceptometer employing a mutual inductance coil system with a closed cycle refrigerator.

## 3 Model Calculation

The measured susceptibility showed a field-dependent behaviour, especially at temperatures near $T_C$. The $\chi_1''$ had a single maximum and shifted to lower temperatures as the applied field increased. These results show that the Bean model is quite applicable to the qualitative description of the material. In the Bean model, the critical current density, $J_c$, is assumed to be independent of local magnetic fields. For the disc-geometry, the magnetization can be given as

$$M = -\chi_0 H_a S(H_a/H_p) \tag{1}$$

where $H_a$ is the applied and $H_p$ is the least magnetic field penetrating to the centre of the disc. The function $S(x)$ is given by

$$S(x) = \frac{1}{2}\left[\cos^{-1}\left[\frac{1}{\cosh x}\right] + \frac{\sinh x}{\cosh^2 x}\right] \tag{2}$$

as in [7]. Here, $\chi_0 = 8R/3\pi d$ is a value for a complete flux shielding of a disc with thickness $d$ and radius $R$, which exhibit perfect diamagnetism. If the applied ac field $H_{ac}$ modulates between $-H_m$ and $+H_m$, the magnetization for the descending and ascending portions can be given, respectively, as in [8]

$$M = -\chi_0 H_m S(H_m/H_p) + \chi_0 H_m S(H_m - H_a) S((H_m - H_a)/2H_p), \tag{3a}$$

$$M = \chi_0 H_m S(H_m/H_p) - \chi_0 H_m S(H_m + H_a) S((H_m + H_a)/2H_p) \tag{3b}$$

By using of these magnetization equations, harmonic susceptibilities ($\chi_n = \chi_n' + i\chi_n''$) are calculated as

$$\chi_n' = \frac{1}{\pi H_{ac}} \int M(t)\sin(nwt)\,d(wt), \tag{4a}$$

$$\chi_n'' = \frac{1}{\pi H_{ac}} \int M(t)\cos(nwt)\,d(wt) \tag{4b}$$

in-phase and out-of-phase components of harmonic susceptibilities, respectively.

## 4 Results and Discussion

Figure 1 shows the full penetration field, $H_p$, versus the peak temperature, $T_p$. At the peak values of $\chi_1''/\chi_0$, ac field amplitudes are equal to the full penetration $H_p$. A function of the form $H_p = H_\alpha(1-t)^\beta$, $t = T/T_C$ with parameters $H_\alpha \approx 8.85 \times 10^8$ (A/m) and $\beta \approx 3.64$ fits best to the data observed. The lower temperature part of the curve is obtained by extrapolation. The value of $\beta$ is similar to 1.86 for BSCCO [9] and 3.34 for $MgB_2$ [10].

In Fig. 2, we show the measured fundamental susceptibility at various ac field amplitudes. The inset plot in the figure indicates the out-of-phase component of the fundamental susceptibility. All the measurements reported are normalized at 50 K. The peaks shift to lower temperature with increasing ac field amplitudes. The diamagnetic onset temperature of the superconducting transition is found to be 90 K. The diamagnetic onset temperature is constant at different fields. This temperature is defined as the start of

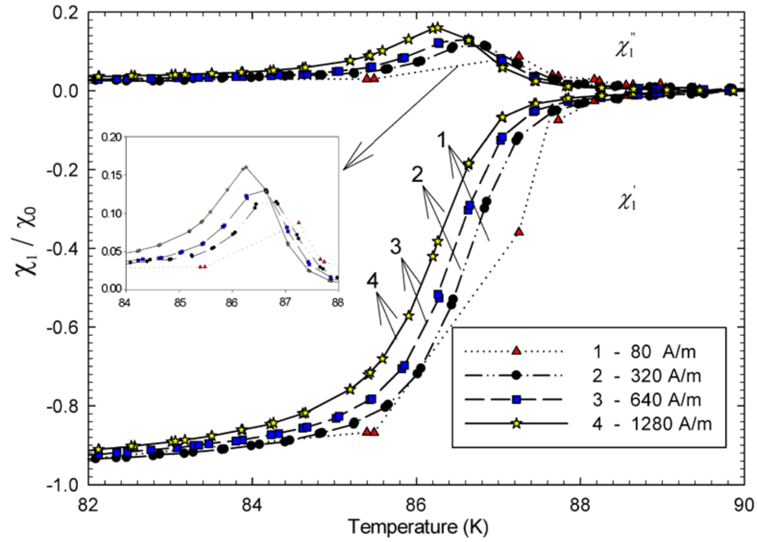



**Fig. 2** Experimental measurements of fundamental harmonic susceptibilities for $H_{ac} = 80$, 320, 640 and 1280 A/m (rms) at $f = 81$ Hz

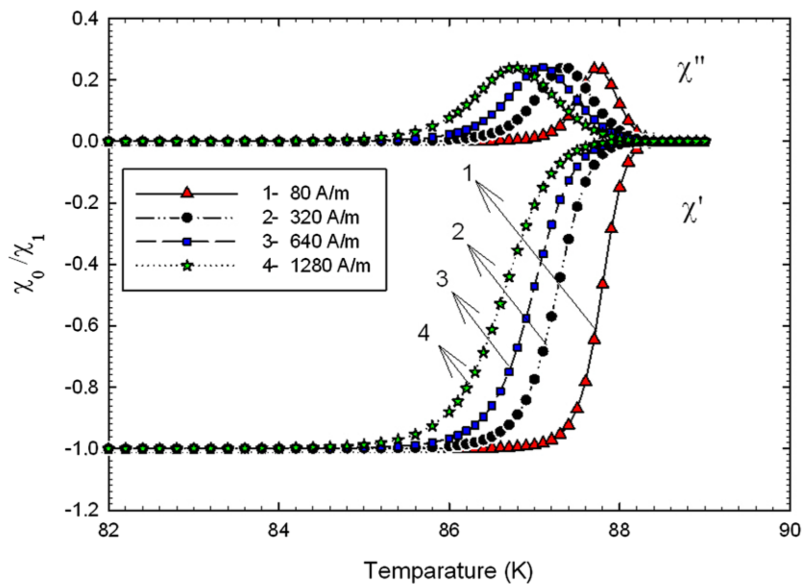


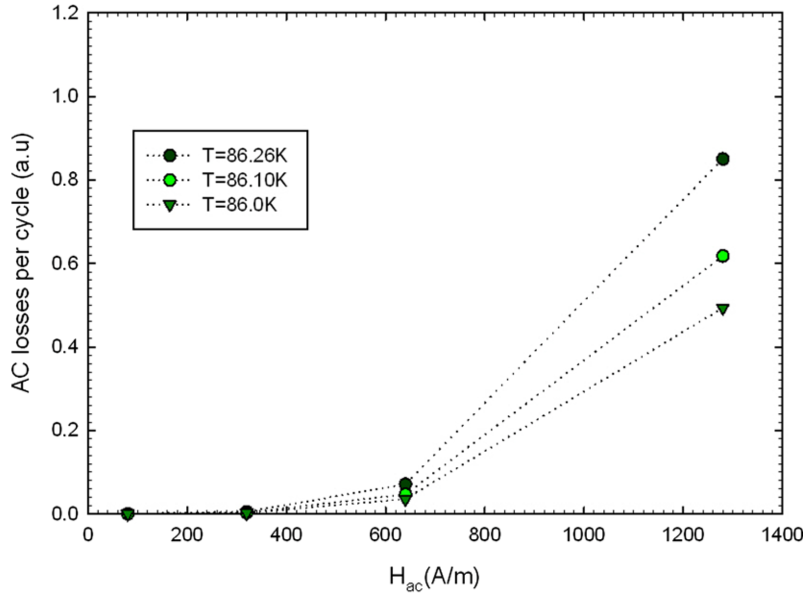

**Fig. 3** Numerical solutions of fundamental harmonic susceptibilities from (4a) and (4b) versus temperature for 80, 320, 640 and 1280 A/m (rms)

diamagnetism and attributed to the bulk superconductivity. Fundamental susceptibility shows a typical single-step transition and a sharp superconducting transition in our sample. This result is similar to that of a bulk $MgB_2$ [10] and bulk YBCO [11]. The peak temperature, $T_p$ is 87.30, 87.10, 86.80, and 86.38 K for ac fields of 80, 320, 640, and 1280 (A/m), respectively.

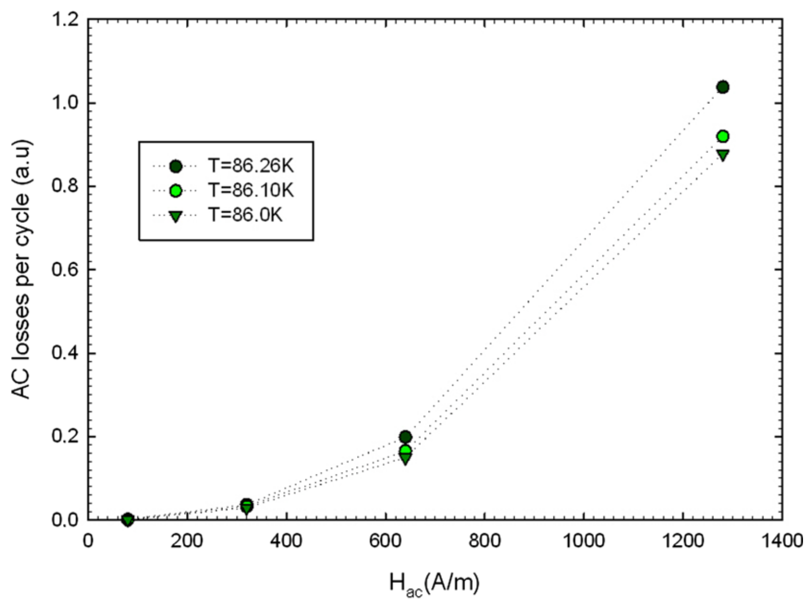
Figure 3 displays the calculated fundamental susceptibility. The theoretical calculation was carried out by Bean model with the fitting equation $H_p = H_\alpha(1-t)^\beta$ for disc-geometry. The results obtained from model calculations exhibit that, the peak temperature, $T_p$ are 87.70, 87.40, 87.10, and 86.70 K for ac fields of 80, 320, 640, and 1280 (A/m), respectively. As $H_{ac}$ increases, the peak moves to lower temperature, but the height of the peak of imaginary part is not affected. As can be seen in Fig. 2 and Fig. 3, the experimental values are in agreement with model calculations.

The calculated measured ac losses versus ac field amplitude for three temperature ($T = 86.26$, 86.10, and 86.00 K) are shown in Fig. 4a and 4b, respectively. Although the sample is a melt-textured single crystal, the weak link can cause ac losses. The weak links may be due to imperfections in the material or some poorly oxygenated regions which are non-superconductive or become nonsuperconductive with applying magnetic fields. Another source of the weak links may be due to microcracks generated by non-uniform oxygen diffusion [11]. It can be found from Fig. 4 that ac losses exhibit a parabolic curvature as a function of $H_{ac}^2$. Consequently, the results are in good agreement with theory.

**Fig. 4** Theoretical (**a**) and experimental (**b**) ac losses as a function of $H_{ac}$ for three different temperatures




(a)




(b)

## 5 Conclusion

The superconducting bulk YBCO prepared by a melt growth method was characterized by AC susceptibility measurement. The measured fundamental susceptibility was calculated by using of the Bean model with the fitting parameters. AC losses were also calculated at the same fixed temperatures. As a result, the model calculations were in qualitative agreement with the corresponding experimental measurements. In addition, a suitable temperature dependence for the penetration field $H_p(T)$ was given.

## References

1. Gömöry, F.: Supercond. Sci. Technol. **10**, 583 (1997)
2. Bean, C.P.: Rev. Mod. Phys. **36**, 31 (1964)
3. Kim, Y.B., Hempstead, C.F., Strnad, A.R.: Phys. Lett. **9**, 306 (1962)
4. Chen, D.X., Goldfarb, R.B.: J. Apply. Phys. **66**(6): 2489 (1989)
5. Ishida, T., Goldfarb, R.B.: Phys. Rev. B **41**, 8937 (1990)
6. Dogan, F.: J. Eur. Ceram. Soc. **25**, 1355 (2005)
7. Mikheenko, P.N., Kuzovlev, Yu.E.: Physica C **204**, 229 (1993)
8. Clem, J.R., Sanchez, A.: Phys. Rev. B **50**, 9355 (1994)
9. Güçlü, N., et al.: Phys. Status Solidi (a) **201**, 996 (2004)
10. Güçlü, N., et al.: Mod. Phys. Lett. B **10–12**, 691 (2003)
11. Wang, J., et al.: Physica C **304**, 191 (1998)