Characterization of a Cylindrical Superconductor Disk Prepared by the Wet Technique with Microstructure Analysis and Levitation Force Measurements Using a Permanent Magnet

I. Karaca*

Department of Physics, Faculty of Science and Arts, Niğde University, Niğde 51200, Turkey

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The levitation force between a cylindrical superconducting disk (CSCD) and a permanent magnet \((B_r = 0.15 \, \text{T})\) in the zero-field-cooled (ZFC) regime has been investigated at liquid nitrogen temperature (77 K). The CSCD showed a lower repulsive force. It was considered that the changes in the levitation force are related to the grain orientation, the homogeneity, and the number of the pinning centers in the samples. From the structural analysis, it was found that the volume percentages of the Bi-2223 and Bi-2212 phase are 81% and 19% in the CSCD, respectively. The calculated \(a\) and \(c\) lattice parameters of the Bi-2212 and Bi-2223 phases are \(a=b=5.4055 \, \text{Å} \) (Bi-2212), \(5.4102 \, \text{Å} \) (Bi-2223), and \(c=30.7522 \, \text{Å} \) (Bi-2212), \(37.0327 \, \text{Å} \) (Bi-2223), respectively.

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I. INTRODUCTION

High temperature superconducting (HTS) material has attractive potential applications due to its magnetic levitation property, e.g., a levitated small magnet over a HTS disc cooled by liquid nitrogen. This stable levitation phenomenon can be accounted for by the trapped magnetic flux within the superconductor that originated from the diamagnetism (or Meissner effect) of superconductors [1].

HTS makes it easy to directly watch this interesting phenomenon, and has demonstrated tremendous potential for several fascinating applications such as magnetic bearings, magnetic levitation, magnetic suspension, and other magnetic force related devices [2]. The magnetic force between HTS materials and permanent magnets (PMs) has been studied by several researchers to further the basic understanding of superconductivity [3–5]. The force calculations were based upon the critical-state model of Bean [6]. The results of this investigation confirms the suggestions that the lateral force is due to flux trapping. Johansen et al. [7] extended these results by using a more realistic field profile to fit the experimental results. The Bean model has also been applied to explain the levitation force of the experimental measurements [8].

The levitation force between a superconductor and a magnet can be calculated by
the following formula:

\[ F = \int_v (m \nabla) H \, dv. \]  

(1)

The equation can be simplified in one dimension as

\[ F = m \frac{dH}{dx}, \quad (m = M v, M = A J_c r), \]  

(2)

where \( m \) is the magnetic moment of a superconductor, \( dH/dx \) is the magnetic field gradient produced by the external field, \( M \) is the magnetization per unit volume, \( A \) is a constant depending on the sample geometry, \( J_c \) is the critical current density of a superconductor, and \( r \) is the radius of a shielding current loop. This indicates that it is necessary to have \( r, J_c, \) and \( dH/dx \) as large as possible to acquire a high levitation force [9]. Many workers have studied and reported on the theoretical details between a superconductor and a permanent magnet (PM) [10–13].

In this study, a cylindrical superconductor disk, produced by the wet technique, microstructure characterization made by X-ray powder diffraction (XRD) analysis and magnetic properties, in the zero-field-cooled (ZFC) regimes, was investigated by using a PM.

II. EXPERIMENTAL DETAILS

The starting material was the powder of the nominal Bi_{1.84}Pb_{0.34}Sr_{1.91}Ca_{2.03}Cu_{3.06}O_{10} compound, which was synthesized by a wet-technique using high-purity (>99.99%) Bi2O3, PbO, SrCO3, CaCO3, and CuO. The powder was calcined at 700 °C for 10 h and pressed into pellets with 225 MPa. The pellets were placed in a preheated furnace at 850 °C for 100 h then directly cooled to room temperature. After the sintering process, the powders, obtained from regrinding the pellets, were pressed at various pressures and times into a cylindrical superconductor disk (CSCD) with diameter \((2r)\) of 13 mm and height \((h)\) of 13.52 mm. The CSCD was placed in a preheated furnace at 815 °C at a rate of 0.1 °C/min for 100 h then directly cooled to room temperature (see Figure 1 for the fabrication process).

XRD patterns were obtained with a Rigaku D/Max-IIIC powder diffractometer using Cu Kα radiation at 40 kV and 30 mA with a step of 0.02° over the range 3–50°. The volume percentages of the Bi-2223 and Bi-2212 phases were estimated by measuring the integrated peak intensities of the major XRD peaks.

Magnetic properties were measured in the temperature range 77 K. Measurements were performed in the ZFC regimes in the applied magnetic field, \( B_r = 0.15 \). Magnetic repulsive and attractive forces between the superconductor and a PM were measured using a homemade levitation measuring device. As displayed in Fig. 2, a Nd-B-Fe permanent magnet (1.6x1.4x0.34 cm³ and \( B_r = 0.15 \) T) was put on the plate of a sensitive electronic scale. The CSCD sample (13 mm in diameter) was immobilized at the bottom of a liquid
FIG. 1: A schematic representation of the heat treatment of cylindrical superconductor: (a) sintering and (b) annealing process.

nitrogen-filled receptacle which is movable in the vertical direction (the CSCD and PM are symmetrically fixed on the same line.) This receptacle was then placed just above the plate of the balance without touching it. Thus, the observed weight change of the magnet directly reflected the magnetic force induced in the system [14].

III. RESULT AND DISCUSSION

The volume percentages of the Bi-2223 and Bi-2212 phases were estimated by measuring the integrated peak intensities of the major XRD peaks (this can be seen in Fig. 3). The room temperature XRD diagram indicates the presence of a large amount of the high-Tc (2223) phase. The calculated volume percentage of characteristic peaks was used for Bi-2223, the peaks of (002) and (0010) with $2\theta = 4.7^\circ$ and $24.04^\circ$, and also for Bi-2212 at (002) and (008) with $2\theta = 5.7^\circ$ and $23.22^\circ$, respectively [15–17]. In this work, we have also used the characteristic peaks for the estimation of the volume fractions of the phases, namely,
FIG. 2: Levitation force measurement system.

FIG. 3: XRD patterns of annealed CSCD. The indices H and L in the assignment of the peaks denote the high-$T_c$ (2223) and low-$T_c$ (2212) phases, respectively.
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FIG. 4: Typical hysteretic loops of the axial levitation force between the permanent magnet and CSCD.

\[
\text{Bi} - 2223(\%) = \frac{\sum I_{(2223)}}{\sum I_{(2223)} + \sum I_{(2212)}} \times 100,
\]

\[
\text{Bi} - 2212(\%) = \frac{\sum I_{(2212)}}{\sum I_{(2223)} + \sum I_{(2212)}} \times 100,
\]  

where \( I \) is the intensity of the present phases [18, 19].

As can be seen from Fig. 3, the CSCD consisted of a mixture of low-\( T_c \) (Bi-2212) and high-\( T_c \) (Bi-2223) phases, and the calculated value of the volume percentages of Bi-2223 and Bi-2212 phase are 81% and 19% in the CSCD, respectively. The CSCD sample exhibits a weak inter-granular coupling, hence the weak inter-granular critical current density is a crucial parameter for a HTS [20]. The lattice parameters are calculated by taking into account all the tetragonal structure. The calculated \( a \) and \( c \) lattice parameters of the Bi-2212 and Bi-2223 phases are \( a = b = 5.4055 \, \text{Å} \) (Bi-2212), 5.4102 Å (Bi-2223), and \( c = 30.7522 \, \text{Å} \) (Bi-2212), 37.0327Å (Bi-2223), respectively.

The results of the levitation force have generally been measured in a ZFC process, a few investigations were done in the field cooled (FC) process [21]. We have studied the superconducting transition of a CSCD sample produced by a wet method in a PM employing the ZFC process. For the ZFC process, the maximum and repulsive force value is obtained at zero separation distance. The force can be written from Equation (2) as \( F = m(dH/dx) \), where \( m \) is the magnetic moment related with the magnetization \( M \) and the volume of the superconductor and \( dH/dx \) is the field gradient produced by the magnet. Due to the magnetic stress between the trapped field in the sample and the PM, an attractive force
occurs when the sample is moved away from the PM. This result can be attributed to the number of pinning centers in the sample, which results in an increase of trapped magnetic field inside the samples. In addition, the levitation force is a function of the grain size and crystallographic orientation. Moreover, the weak-links and cracks present in samples result in a small levitation force [20].

It can be seen in Fig. 4 that the interaction force between a CSCD and a PM always shows a F-Z hysteresis loop during the descending and ascending process. This corresponds to the magnetization of the CSCD by mechanically moving the PM (or CSCD) to and away from the CSCD (or PM) [21]. The interaction force, between a CSCD and a permanent magnet (PM), was generated from the interaction between the magnetic field and the induced current in the CSCD. The force is mainly dependent on the properties of the CSCD and the magnetic field distribution of the magnet. For a bulk superconductor, the levitation force is dependent on many parameters, such as the critical current density and grain radius, grain-orientation, thickness of the sample, and the cooling temperature. For a magnet, the levitation force is closely related with the magnetic flux density, magnetic field distribution, etc. But for a given pair of bulk superconductor and PM, it is known that the same levitation force can be obtained at a gap distance between the superconductor and the magnet, because of the magnetization history of the superconductor, by a mechanical descending and ascending process of the magnet during the axial levitation force measurement state [21]. The low levitation force of sintered superconductor materials can be attributed to two intrinsic material problems of a superconductor. The first is the grain boundary weak-link problem and the second is the weak flux pinning problem. In order to resolve these two problems, different material processing techniques have been developed [1].

IV. SUMMARY

It was observed that a superconductor improves the weak-link behavior of the superconducting grains. The ZFC sample showed that the sample has low quality with weak-link characteristics. A typical hysteresis loop of the axial levitation force between the permanent magnet and the CSCD showed the lower repulsive force. This phenomenon is attributed to the fact that the wet technique causes the production of lower dense samples [22], and is caused by a lower critical current density [23] and by a lower levitation force. It is considered that the changes in the levitation force are related to the grain orientation, the homogeneity, and the number of the pinning centers in the samples [24].

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* Electronic address: ikaraca38@hotmail.com