Materials, Characterization, and Application of Single-Grained Y-Ba-Cu-O Superconductors

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Single-Grained Y-Ba-Cu-O (YBCO) high temperature superconductor (HTS) with diameter up to several centimeters has been produced. This HTS material can be used for magnetic levitation, magnetic shielding, and field trapping magnet. The materials processing techniques, such as melt-texturing and seeding of this single-grained YBCO materials will be reported. The principles regarding magnetic levitation and trapping, such as field intensity, field distribution, super-current model, etc., in this single-grained YBCO will be discussed. The effect of high energy particle irradiation on the $J_c(H)$ and field trapping enhancement will be reported. Potential applications of large grain YBCO materials will also be discussed.

Keywords: high temperature superconductor, Y-Ba-Cu-O superconductor, single grained, melt-textured process, seeding, flux trapping magnet, flux shielding, magnetic levitation, critical current density

I. Introduction

The potential economic benefit to operate devices using high temperature superconductor (HTS) materials at temperature near 77 K is the main incentive of HTS studies. The first rush was the attempt to replace Low Temperature Superconducting (LTS) wires with HTS wires for bulk applications. However, polycrystalline $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO) samples suffer the drawback of low intergranular current density $J_c(H,T)$ of 10^1 to 10^2 A/cm² at 77 K. Various processing methods (including pressing, magnetic alignment, Ag addition, etc.) have been explored with limited improvement. This low J_c is due to the well known weak-link phenomenon associated with grain boundaries in polycrystalline YBCO materials. The Bi-Sr-Ca-Cu-O (BSCCO) system has a better mechanical performance and less weak-link problem compared with that of YBCO system. In the last few years, there were significant progress in fabrication of long length BSCCO wires/tapes with relative high critical current densities J_c of $\sim 10^{4.5}$ A/cm² at 77 K, 0 Tesla. However, the magnetic flux motion problem due to intrinsic low pinning force in BSCCO system causes significant flux leaking at temperature above 30 K, and $J_c(H,77K)$ drops 3 to 4 orders magnitude from $10^{4.5}$ A/cm² at 0 Tesla to $10^{1.2}$ A/cm² at 1 Tesla at 77 K. The deterioration of $J_c(H)$ within an external magnetic field restricts BSCCO wire's application at relatively low temperatures range, i.e. below 30 K.

It is generally felt that application of bulk HTS is limited by two intrinsic materials problems described

above, i.e. grain boundary weak-link (typically in YBCO grain boundaries) and low pinning forces (typically in BSCCO materials). As will be described in this paper, the single-grained Y-Ba-Cu-O superconductors exhibit properties which can by-pass both intrinsic material problems described above and could be the first bulk HTS materials for practical applications.

The single-grained Y-Ba-Cu-O superconducting materials have excellent magnetic levitating, magnetic field trapping, and magnetic shielding properties. Recent studies reported that magnetic field up to 7 Tesla at ~ 50 K or up to 5 Tesla at 65 K had been trapped within an irradiated single-grained Y-Ba-Cu-O sample sets. For un-irradiated samples, magnetic field up to 2 Tesla at 65 K had been trapped[1-5]. A recent report by Paul C.W. Chu indicated that magnetic field up to 18 Tesla had been shielded at 4 K by single-grained YBCO samples[6-8]. Magnetic field levitation force of 1.5 N and stiffness of 5 N/mm of the single-grained YBCO samples had been measured [9].

On the other hand, a HTS magnet wound by long length BSCCO tapes of about 15 cm O.D. and 2 cm I.D. can only generate about 0.3 Tesla at 77 K, 1.5 Tesla at 20 K, and 2.6 Tesla at 4 K [10]. This large difference (near a factor of 10) in magnetic field generated by these two types of HTS materials (single grained YBCO vs. BSCCO wires) can be attributed to the superior intrinsic superconducting property of single-grained YBCO materials.

II. Processing of Single-Grained Y-Ba-Cu-O Superconducting Materials

Two processing techniques are involved in the growth of single grained YBCO materials, i.e. melt-texturing (MT) processing and seeding technique. A typical MT process includes heating pre-sintered YBCO sample to 1100 °C followed by slow cooling from 1050 °C to 900 °C at a rate of 1 °C/hr. Finally, a relative long oxygen annealing at 400-600 °C for 1 week or more is required to fully oxygenate the sample [11-13]. Fig. 1 shows the SEM micrograph of a MT-YBCO samples starting with stoichiometric $\text{YBa}_2\text{Cu}_3\text{O}_7$ (Y123) powders. The white particles are non-superconducting Y_2BaCuO_5 (Y211) precipitates and the matrix (appears as dark) is the superconducting Y123 phase. The well-aligned dark lines are residual BaCuO_2 phases of un-reacted liquid phase during slow cooling process, which is parallel to the a or b orientation of Y123 crystal structure.

Fig. 1. Scanning electron micrograph of a MT-YBCO sample started with stoichiometric $\text{YBa}_2\text{Cu}_3\text{O}_7$ powder.

Fig. 2. SEM micrograph of a MT-YBCO sample with 6 %wt. of Y_2O_3 addition. By comparing with that in Fig. 1, the difference in Y211 precipitate size is obvious.

Fig. 2 shows the SEM micrograph of a MT-YBCO sample with 6 %wt. of Y_2O_3 addition. It is clearly shown in Fig. 2 that the size of Y211 precipitate has been reduced and the number of Y211 precipitate has been increased. Quantitative analysis of Y211 precipitate size distribution and the count of Y211 numbers are shown in Fig. 3. The distribution of the Y211 precipitate narrows to the small size range and the number of the Y211 precipitates increases by a factor of several times. It is believed that the interface between Y211 precipitates and Y123 creates effective pinning center which enhances the $J_c(H, T)$ [14]. Various attempts, including different temperature profiles (e.g. melt quench), addition of excess of Yttrium by Y_2O_3 or Y_2BaCuO_5 , Pt, Ag, BaSn, etc. have been explored to modify the microstructure and superconducting properties in Y-Ba-Cu-O samples. $J_c(1T, 77K)$ in the range of 5,000 to 30,000 A/cm² have been reported.

Fig. 3. Quantitative analysis of Y211 precipitates with different amount of Y_2O_3 addition.

This MT process only enhance the crystal growth condition, i.e. to increase the grain size of Y-Ba-Cu-O materials. The typical MT processed YBCO samples are still polycrystalline. Their grain orientation and size are still randomly distributed. The control of YBCO crystal nucleation by introducing a Sm-Ba-Cu-O seed was first reported by Morita et. al.[15]. With this seeding method, large single-grained Y-Ba-Cu-O materials can be made with pre-determined orientation.

Since the matrix phase is a continuous superconducting phase, there is no grain boundary acting as weak link to block the superconducting current. Therefore, single grained YBCO sample can be classified as a quasi single crystal superconducting materials, although there are second phase precipitations within the single grained YBCO sample. Fig. 4 shows a single grained YBCO sample with over 3 cm diameter can be

produced with high yield by combining the melt-textured and seeding technique.

III. Characterization of Single-Grained Y-Ba-Cu-O Superconductors

One method to characterize the single grained YBCO sample is to measure the trapped magnetic field after field cooled or zero field cooled within an external field. Traditional magnetometers, such as vibrating sample magnetometer (VSM) and superconducting quantum interference device (SQUID) are not able to measure large sized samples. The trapped magnetic field is generated by induction of persistent super-current loops in the superconductor. In other word, the single grained YBCO sample can be viewed as a stack of pancake shaped superconducting persistent current loops. The maximum trappable field $B_{t,max}$ is a function of the $J_c(H,T)$ and grain size $f(d,t)$.

$$B_{t,max} \sim J_c(H,T) f(d,t) \quad (1)$$

where $J_c(H,T)$ is the critical current density at the magnetic field H and temperature T . And $f(d,t)$ is geometric function related to grain diameter d and thickness t [16]. Fig. 5 shows the contours of the trapped magnetic field intensity of a single grained YBCO sample with 2.5 cm diameter and 0.6 cm thick. The $B_{t,max}$ is about 5.6 kG.

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Fig. 4. A single grained YBCO sample, processed by combining melt-textured and seeding techniques, grows to a grain size larger than 3 cm diameter.

For samples with more than one superconducting grains, the weak-link effect at the grain boundary will block the persistent super-current loop and more than one peaks will be shown on the field mapping diagram. Fig. 6 shows a typical multi-peak magnetic field profile measured from an un-seeded MT-YBCO sample.

It is believed that the levitation force is also related to the $J_c(H,T)$ and superconducting grain size $f(d,t)$. From materials point of view, the fundamental requirement for both the trapped field and levitation force is identical.

Fig. 5. The mapping of the trapped magnetic field intensity of a single grained YBCO sample with 2.5 cm diameter and 0.6 cm thick. The uniformly spaced contour indicates that the super-current density $J_c(H,T)$ is a constant value. It also indicates that the superconducting properties is uniform across the entire sample. The $B_{t,max}$ is about 5.6 kG.

Fig. 6. A typical multi-peak magnetic field profile measured from an un-seeded MT-YBCO sample. The insert shown in the bottom schematically reveals the super-current loops which generate the field profile above. In between these two current loops, a barrier (physically, which can be a grain boundary or crack) exists that blocks these two loops to become one bigger loop.

IV. Effect of high energy particle irradiation on $J_c(H,T)$

The effect of high energy particles irradiation on the $J_c(H,T)$ had been studied extensively. However, most of these studies were conducted on single crystals, which were very small in size and had little value for practical applications. Two types of irradiation experiments on bulk, large size melt-textured or single grained YBCO samples had been conducted. Light ions ($_1H^+$, $_3He^{++}$) at 200 MeV increase $J_c(H,77\text{ K})$ by 3 to 5 times to about 40,000 A/cm² at 77 K, 0 T [17].

It has been shown in YBCO single crystal that columnar defect due to heavy ion bombardment acts as a more effective pinning centers[18]. Nevertheless, the heavy ion has a very short penetration depth which would not penetrate through the thick single grained sample. Recently, an internal Uranium fission method has been developed to overcome this problem. Uranium oxide compound was added and grown within the single grained YBCO samples. Then, these samples were irradiated by thermal neutron to cause fission reaction. Since the thermal neutron has no charge that can penetrate deep into the sample, thick single grained YBCO samples can be irradiated throughout. It is well known that U/n fission reaction releases about 210 MeV energy, and each Uranium atom will fission into two atoms with atomic number in the range of 90 and 140 respectively. Calculation shows that the total fission track length will be about $15 \mu\text{m}$. Fig. 7 shows the preliminary result of this internal Uranium method. $J_c(0.5\text{T}, 77\text{K})$ increases monotonically with the neutron fluence up to $85,000 \text{ A/cm}^2$. Further experiments are still in progress.

Fig. 7. The preliminary result of the internal Uranium method shows a $J_c(0.5\text{T}, 77\text{K})$ increases monotonically with the neutron fluence up to $85,000 \text{ A/cm}^2$. The $J_c(0.5\text{T}, 77\text{K})$ before irradiation is about $15,000 \text{ A/cm}^2$.

V. Potential Applications and Summary

The single grained YBCO material has very unique magnetic characters including magnetic levitation/suspension, magnetic field trapping, and magnetic shielding properties. These characters are attributed to the elimination of grain boundary weak link problem of YBCO materials. Besides, the pinning force and pinning center densities of YBCO materials have also been improved either by physical (e.g. high energy irradiation) or by chemical (e.g. Y_2O_3 , Pt addition) methods. On the other hand, the BSCCO materials are still restricted by the intrinsic low pinning force problem that high J_c at high field is not available near the liquid Nitrogen temperatures. Before BSCCO's low pinning force problem can be resolved, single grained YBCO

material seems to be the only useful HTS material that has the required superconducting properties at 77 K.

A broad range of applications have been proposed and some of them have been built and tested [19]. For example, both Japan and U.S. are using these single grained Y-Ba-Cu-O materials to construct frictionless superconducting levitation bearing or flywheel prototypes with a levitation weight up to several tens of kilograms. Other potential applications, such as, magnetic levitation transportation system, clamp, vibration absorber, magnetic clutch, etc., have been studied.

The magnetic suspension phenomenon, first observed by M.K.Wu et. al. in a small YBCO/Ag HTS sample [20], has now been able to suspend a much heavier weight. Fig. 8 shows a globe (with a permanent magnet attached to the top) weight about 2 Kg can be suspended under a single grained YBCO sample located within the liquid nitrogen cup on the top.

Fig. 8. A suspending globe used to demonstrate the unique HTS/magnet suspending effect used in building frictionless bearing and flywheel.

Very high continuous magnetic field up to 7 Tesla has been trapped in single grained YBCO samples [4]. Before this record was set, the LTS magnet, which required liquid Helium to operate it, was the sole material to generate this high field. The high field trapping capability of single grained YBCO material opens a new route to generate high field at temperatures near liquid Nitrogen range. Potential applications such as motor/generators, smaller sized magnetic resonance imaging magnet, dent puller, etc. had been proposed. The high magnetic shielding properties of single grained YBCO samples have been proposed to be used in magnetic shielding room for medical diagnosis or passenger compartment of MEGLEV. It is believed that many new

applications will be evolved when the materials processing techniques have further been improved.

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