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Thermal and mechanical properties of high T_c bulk superconductors and their applications

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Abstract

The Iwate CREATE (Collaboration of Regional Entities for the Advancement of Technological Excellence) Project, "Advanced Applications of Magnetic Field", started since October 1999, aims a creation of a COE and a new industrial area in the field of magnetic field applications and magnetic measurements. The basic study group in this project is making extensive measurements on mechanical properties (strength, toughness and so on) and thermal properties (thermal conductivity, thermal diffusivity, Seebeck effect, and so on) of melt-textured high T_c bulk superconductors in order to build up a database and feed it back to the higher performance bulk material processing technique in the future. This group also studies the magnetizing technique for these materials and realization of various magnetic field environment for the application to the magnetic separation, highly oriented polymer film and so on.

Keywords: Iwate project; Bulk superconductor; Mechanical properties; Thermal properties; Pulsed field magnetization; Magnetic separation

1. Introduction

The CREATE (Collaboration of Regional Entities for the Advancement of Technological Excellence) Project, initiated in 1997, aims a creation of a COE and a new industrial area in each regions. So, the Iwate CREATE project "Advanced Applications of Magnetic Field", started in October 1999, aims a creation of a COE and a new industrial area in the field of magnetic field applications and magnetic measurements. There are three major groups. (A) Applications of strong magnetic field, (B) magnetic measurement techniques, (C) basic study group.

The basic study group is making extensive measurements on mechanical properties (strength, toughness, and so on) and thermal properties

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(thermal conductivity, thermal diffusivity, Seebeck effect, and so on) of melt-textured high T_c bulk superconductors in order to build up a database (DB) and feed back it to higher performance bulk material processing techniques in the future. This group also studies the magnetizing technique for these materials and realization of various magnetic field environment for the application to the magnetic separation, highly oriented polymer film preparation, and so on.

In this paper, a part of the results of mechanical and thermal property measurements on various melt-textured high T_c bulk materials, studies of magnetizing techniques and magnetic field generation by them, and an experiment of high gradient magnetic separation (HGMS) by bulk superconducting magnets are reported.

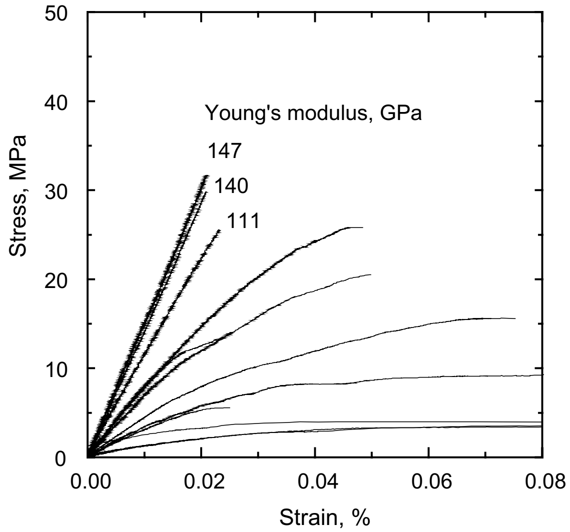

Fig. 1. Stress–strain curves of Sm–Gd(1 2 3) samples. Specimens with high tensile strength hold the linear relationship, Young's modulus of each sample is given in the figure, up to fracture. The stress tend to saturate after linear relationship in the initial stage in other specimens with relatively low strength.

2. Mechanical properties of bulk superconductors

The parameters of the mechanical properties of the bulk superconductors have been evaluated. They are the hardness number and the fracture toughness by Vickers hardness test and the elastic parameters, the fracture strength and the fracture toughness by tensile test and bending test. Some of the results are to be reported in these Proceedings.

Highly c-axis oriented $REBa_2Cu_3O_y$(1 2 3)/10–40 mol% RE_2BaCuO_5(2 1 1)/small amount of Pt with or without 10 wt.% Ag single grain bulk superconductors fabricated by top seeded melt growth method were used (RE: Y, Sm, Gd, Sm–Gd and Nd–Eu–Gd (NEG)).

Tensile test [1–4]: For the tensile test, $3\times3\times4$ mm^3 specimens were cut out from the samples so as to the longitudinal axis is in the direction of a, b or c axis. A closed loop electro-hydraulic testing machine was used. Tests have been conducted at 293 and 77 K. Strains of the specimens during the test was measured by attaching a pair of strain gauges.

Stress vs. strain curves varied widely, presumably, depending on the defects included in the specimen. For Sm–Gd(1 2 3) sample, the maximum value of Young's modulus, E, was 147 GPa and the higher the tensile strength was, the higher the E was. Although specimens with high tensile strength hold the linear relationship up to fracture, the stress tend to saturate after linear relationship in the initial stage in some specimens with relatively low strength (Fig. 1). This indicates that the slow crack extension could occur from relatively large defects involved in the samples. The E in all the bulks increased with decrease in the temperature and decreased with increase in the distance from the center of the bulk sample. Anisotropy of E as well as Poisson's ratio associated with crack opening was observed. These elastic constants are necessary for the numerical stress analysis of the bulk materials with complex configuration.

The value of tensile strength, UTS, scattered significantly. Excepting the region very close to the seed crystal, the UTS increased with decreasing distance from the seed at the center of the bulk both in the radial and depth directions (Fig. 2). Although the UTS in NEG(1 2 3) sample increased with decreasing temperature, those in all other bulks decreased with the temperature. The temperature dependence of the UTS is controlled by not only that of the theoretical strength without defects but also the localized stress at the involved

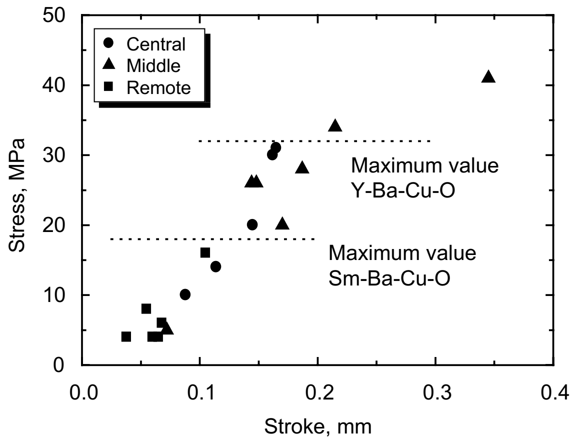

Fig. 2. Tensile strength of Sm–Gd(1 2 3) samples.

defects. The strength distribution of the specimens combined with defect distribution analysis appears to enable the estimation of overall strength of the bulk materials.

3. Thermal properties of bulk superconductors

On designing and manufacturing of cryogenic apparatus using the melt-processed REBaCuO bulk superconductors, it is important to have the knowledge of the thermal and thermo-mechanical properties. These bulks usually consist of the $REBa_2Cu_3O_7$ (RE123) superconducting phase, RE_2BaCuO_5 (RE211) impurity phase and silver (Ag) and platinum (Pt) metals, which can be regarded as a composite superconducting material. It has been found that the contents and the sizes of the RE211 phase and Ag particles strongly influence the critical current density J_c and the magnetic flux trapping ability. The thermal transport properties (thermal conductivity κ, thermal contraction $\Delta L/L$, thermal diffusivity α, thermoelectric power S, etc.) and their anisotropies are also crucially influenced by these quantities. For the application to power current leads of these bulks, the low κ and α values are desirable, but for the application to stronger bulk magnets, the higher heat conduction may be necessary to prevent the temperature rise and the exudation of the trapped flux. The abundant and methodical DB of the thermal properties, however, has not been completed for these bulk superconductors. We constructed the liquid He free measuring station of the thermal properties at the temperature range of 6–300 K and under the magnetic field of 0–10 T using a GM refrigerator and a cryocooler-cooled

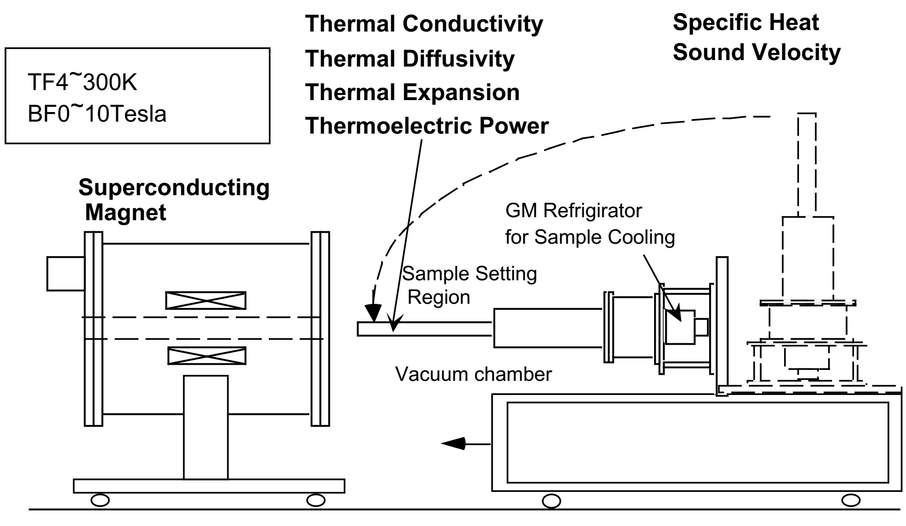

Fig. 3. A view of the liquid He free measuring station for thermal properties.

superconducting magnet as shown in Fig. 3 [5,6]. We have measured the thermal properties (κ, α, estimated specific heat $C(=\kappa/\alpha)$, $\Delta L/L$, S and thermal contact resistance R_c [7]) for the various types of REBaCuO bulk superconductors (RE = Y, Sm, Gd, (Nd, Eu, Gd), etc.) and compared with the superconducting properties [6,8–12].

Fig. 4 shows examples of thermal conductivity for the Ag-doped Sm-based crystals [6]. In Fig. 4(a), the *ab*-plane thermal conductivity κ_{ab} drastically decreased with increasing the content of Sm211 phase X. It has been found that the Ba–Sm substitution occurs and that the low-T_c (or non-superconducting) phase is produced in this system. The substitution effect reduces the crystal quality of the Sm123 superconducting phase and, resultantly, deteriorates the absolute value of κ_{ab} and the κ_{ab} enhancement below T_c, which is in contrast to the Y-based system. In this way, the κ measurement is a valuable tool to investigate the crystal quality and the distribution of the secondary phase in the composite materials. Fig. 4(b) shows the $\kappa_{ab}(T)$ for the $X = 0.1$ specimen under the magnetic field which was applied perpendicular to the *ab*-plane. The κ_{ab} enhancement below T_c is drastically suppressed with increasing applied field, especially for lower field than 5 T. This reduction can be understood as caused by the enhanced phonon scattering by the quasi-particles in the vortex cores. We expect that these data are valuable also for the applications.

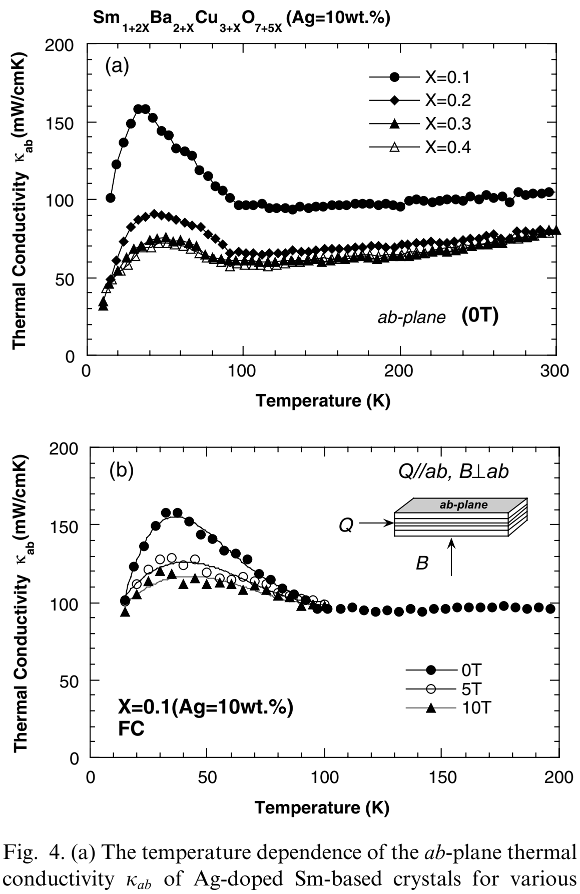

Fig. 4. (a) The temperature dependence of the *ab*-plane thermal conductivity κ_{ab} of Ag-doped Sm-based crystals for various Sm211 contents (zero field). (b) $\kappa_{ab}(T)$ for the $X = 0.1$ specimen under the magnetic field ($B \perp ab$-plane).

4. A superconducting bulk magnet system

The trapped field of melt-textured bulk superconductors has been substantially improved by choosing Sm in place of Y. As was reported by Ikuta et al. [13], the maximum trapped field attained in the Sm–Ba–Cu–O system has reached 9.0 T at 25 K. They pointed out that it is quite effective to use the excellent field trapping property in the temperature range lower than 77 K. So, Sm–Ba–Cu–O bulk samples manufactured by Dowa Mining Co. were adopted to the newly developed superconducting bulk magnet system, as shown in Fig. 5. A pair of bulk samples reinforced by impregnating epoxy resin with glass fibers was mounted on the respective cold stages of the GM refrigerators in each vacuum vessel, and was cooled down to 38 K in a few hours [14].

The bulk samples were magnetized by applying pulsed field by using a magnetizing coil (pulsed field magnetization method, PFM). A magnetizing coil, on the right hand side of magnetic poles shown in Fig. 5, is removed after completing the PFM. Though the flux penetration into the superconductors causes local heating in the sample and subsequently degrades the trapped field, a novel magnetization technique "IMRA method" (iteratively magnetizing pulsed-field operation with reducing amplitudes) effectively enhances the trap-

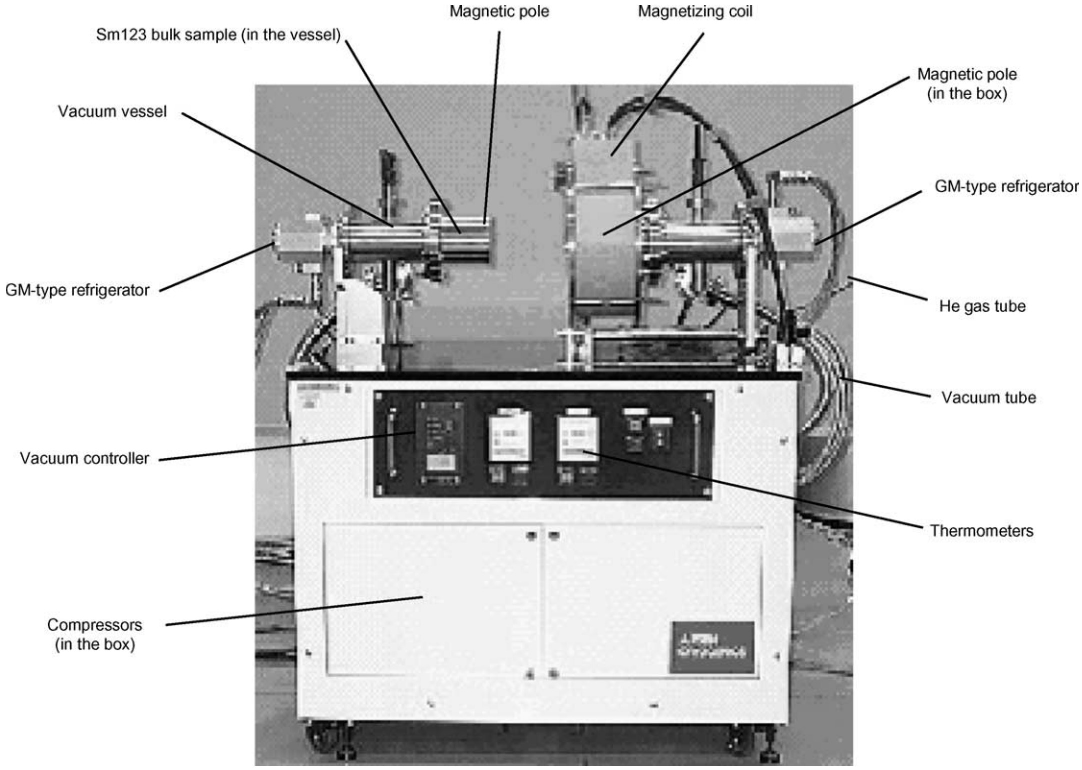

Fig. 5. A photograph of the superconducting permanent magnet system with a magnetizing coil set around the right hand side magnetic pole.

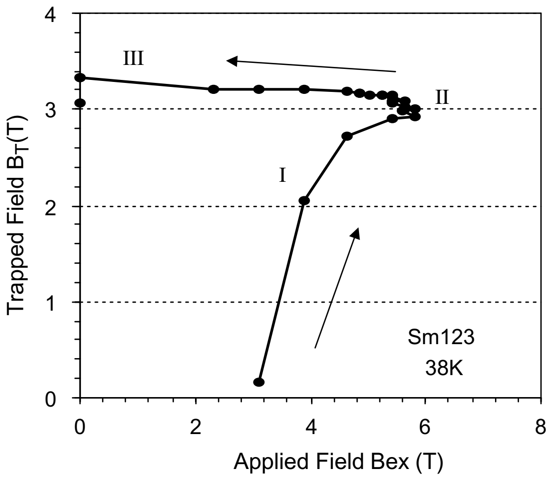

Fig. 6. History of the trapped flux density magnetized by IMRA method at 38 K.

ped field [15]. Fig. 6 shows the history of trapped field by the IMRA method operated at 38 K. The trapped field first increases with increasing applied fields (see I in Fig. 6), then tends to saturate above 5 T (see II). When the pulses with reducing the amplitudes are applied, the trapped field gradually increases and exceeds 3 T (see III).

4.1. Magnetic field distribution

The trapped flux distributions measured by a Hall sensor (F.W. Bell BHA921) along the pole axis as a function of various gap distances are shown in Fig. 7. The maximum trapped field between the magnetic poles has reached 3.15 T. This performance exceeds the maximum value of large-scale electromagnets and is by far stronger than that of conventional permanent magnets such as Nd–Fe–B. The magnetic field in the gaps decreases with increasing gap distance, showing 1.8 T at the center in the case of 20 mm gap distance. The

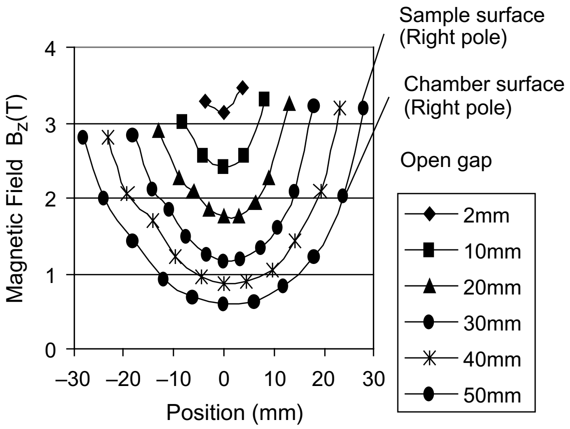

Fig. 7. Magnetic field distribution along the axis of magnetic poles as a function of the gap distances.

following magnetic separation experiment is operated in this open space.

5. HGMS using superconducting bulk magnets

We aim to apply superconducting bulk magnets to a magnetic separation that is to remove dirt or to capture useful materials from slurry by acting the magnetic force to the separating particles.

Fig. 8 shows the photograph of a magnetic separation system using the face-to-face type superconducting bulk magnet system. A separation pipe with magnetic filters is placed between magnetic poles of 20 mm gap. The magnetic flux direction is from left to right hand side and the slurry flows from under to upper side. Using the 500 ppm of α-hematite (Fe_2O_3, averaged diameter: 1 μm) mixed slurry, hematite particles are separated at a flow rate of 0.1–3.0 l/min and a separation percentage is investigated.

Fig. 9 shows the purified samples. No. 1 is original slurry. Nos. 2–6 are the purified sample at a flow rate of 0.1, 0.5, 1.0, 2.0 and 3.0 l/min, respectively. Up to the flow rate of 1.0 l/min, most hematite particles are captured and samples is transparent. For higher flow rate than 1.0 l/min, on the other hand, the particles are leaked from the separation filter because it is saturated, and samples become muddy.

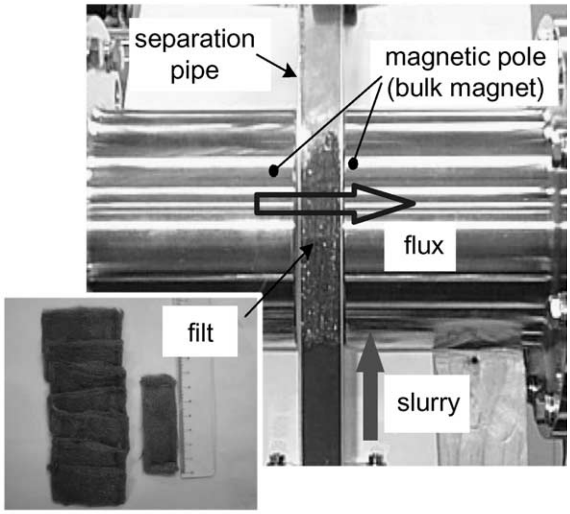

Fig. 8. Magnetic separation system using a face-to-face type superconducting bulk magnets. A separation pipe with magnetic filters is placed between magnetic poles. The magnetic flux direction is from left to right hand side and the slurry flows from under to upper side. The original slurry has muddy color but the separated water becomes transparent.

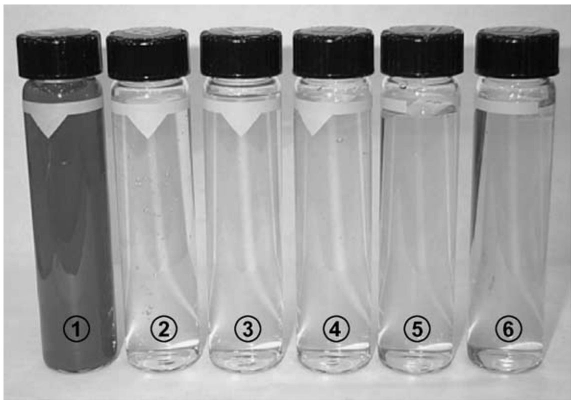

Fig. 9. Comparison of purified samples. No. 1: original slurry. Nos. 2–6: the flow rate is 0.1, 0.5, 1.0, 2.0 and 3.0 l/min, respectively.

Fig. 10 illustrates the relationship between the separation percentage and the flow rate. Up to 0.5 l/min, over 99% of hematite particles is separated. The separation percentage at 1.0, 2.0 and 3.0 l/min is 94.6%, 93.2% and 71.4%, respectively.

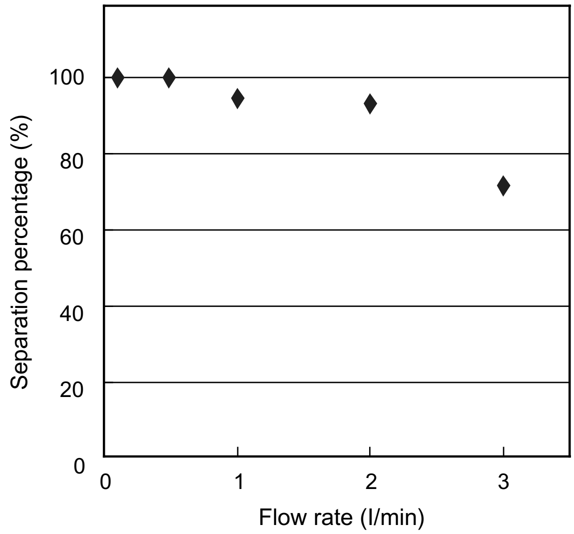

Fig. 10. The relationship between the separation percentage and a flow rate.

6. Summary

(1) In the Iwate CREATE project "Advanced Applications of Magnetic Field", the basic study group is making an extensive study on mechanical and thermal properties of high T_c bulk materials in order to build up a DB and feed it back to higher performance bulk material processing techniques in the future.

(2) The basic study group also studies magnetizing techniques and realization of various magnetic environments for the application to the magnetic separation, highly oriented polymer film preparation, metallic structure control of high temperature spring materials, and so on. Maximum 3 T magnetic field was achieved up to now.

(3) As a first application we made a HGMS experiment, in which weak paramagnetic hematite particles were removed from water.

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