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Strictly application-oriented REBCO bulk fabrication

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Abstract. The ability to produce large-grain REBCO (RE= Y, Rare Earth) bulk superconductors by melt texturing growth has been improved and refined significantly over the last 20 years. Magnetic bearings, transportation systems, and scientific instrumentation are becoming major innovations of HTS bulk materials. Large grain production is dominated by cold top-seeding melt growth (TSMG). For material optimizing we demonstrate strictly application-oriented fabrication close to the final geometry and thus reducing mechanical machining and assembling work. YBCO hollow cylinder design for journal bearings with radial *c* axes orientation are obtained by radial-seeding geometry (RSMG). YBCO ring tiles up 120 mm show a perfect cylinder geometry with in-wall *a*, *b* orientation and radial *c* axes. We report improved electric and mechanical bulk properties and demonstrate great production effectiveness. For achieving high field permanent magnets up to 10 T we compare YBCO bulk and ring geometry. Top/bottom double seeded melt growth (DSMG) grain samples provide better magnetic flux trapping capability and show more homogenous properties.

1. Introduction

Bulk high-temperature superconductors (HTS) in contrast to long-length thin film HTS short after the HTS discovery are combined with a broad spectrum of magnetic applications. Noticeably, REBCO bulk material is significantly application-driven but the costs are not proportional to the field strength provided. The compact design, easy cooling at temperatures between 77 and 50 K and the intrinsic circulating superconducting current enable the production of trapped field magnets (TFM) up to about 5 T without further treatment capacity [1]-[4].

In the present paper we concentrate on attempts to fabricate YBCO bulks in shape and design close to applications. The optimum configuration is thereby already influenced by a geometrical variation of the single or multi-seed configuration. Top seeding methods with SmBCO or NdBCO small seed crystals in the size 3x3 mm² deliver typically disk-like bulks with the supercurrents flowing dominantly in the *a*, *b* plane.

For most applications the external field vector has to angle with the crystallographic *c* axis of a single grain sample to achieve the optimum current density in the crystallographic *a*, *b*, plane. Although the TSMG method yields excellent REBCO single grain results certain applications as journal HTS bearing stators or radial motor configurations reveal geometrical problems associated with a perfect radial *c* axes orientation. Either the TSGM disks are individually machined expensively into a segment shape and assembled into ring geometry. Alternatively, the final radial structure is aimed by a corresponding radial seed structure. For this, the seed crystals are fixed in small groves at the inner or outer surface of a pressed green body ring. We describe the development and use of the radial seeded melt growth (RSMG) technique to promote fast and direct YBCO ring fabrication and application. The fabrication strategy prevents sophisticated machining and assembling to develop economical and clever magnet technologies.

In a second step, we investigate a top/bottom double seed melt growth (DSMG) technique for 30 mm YBCO bulks to improve the electric and magnetic sample homogeneity. Each YBCO is grown from two SmBCO seeds, on top and bottom. The planar orientation given by the azimuthal angle of the two seeds, each to another, are varied from 0° to 45°. The trapped field behavior of the top and bottom crystals of each samples is determined and compared for different azimuthal angles between top and bottom.

According to present bulk activities fabrication and preparation of superconductive permanent magnets to achieve high external field trapping is most prominent. The function and the improvement of compressive stress at REBCO bulk and ring disks by metallic rings (SUS316 or Al alloy) is numerically and experimentally investigated. We studied standard YBCO bulk disks without Ag_2O and mounted them in stainless steel rings. After shrink fitting a 32 x 2 mm SUS316 ring the corresponding trapped field results at 20-30 K and 5-10 T for YBCO disk and ring bulk are compared and discussed.

2. Bulk fabrication experiments and results

2.1 Variable seed geometry: Radial seeding

All YBCO samples are prepared by the well-known melt growth standard process using 75 wt. % Y123, 25 wt. % Y211, and 0.6 weight % ZrO_2. All precursor powders are in-house synthesized from raw materials Y_2O_3, $BaCO_3$, and CuO and are milled to a grain size of 5-20 µm. In the economical process route YBCO single or multi-seed bulk are grown without Ag_2O [4]. Figure 1 displays the conventional YBCO TSMG route by using $SmBa_2Cu_3O_{7-x}$ as seed crystal. Pinning effect in melt-textured samples can be enhanced in several ways: Using extremely fine grained Y211 powder with sub–micrometer grain size or additional doping e.g. by Zn. In figure 1 the typical sample structure is shown, consisting of the four characteristic growth sectors on top separated by four growth boundaries. TSGM samples possess always the *c* axis normal to the growth plane. On the way to a more effective application of REBCO bulks we have been developed a variation of the Sm123 seeding to produce YBCO rings with radial *c* axis distribution. Figure 1, right, displays the radial seed technique schematically together with two YBCO rings of 80 mm and 100 mm in diameter. While the 100 mm ring consists of 10 inner seeds corresponding to 10 YBCO crystals with *a*, *b* plane in the wall, the 80 mm ring has been seeded 8 times on the external rim. Due to that YBCO configuration as stator with a PM rotor assembling of a superconducting journal magnetic bearing is significantly easy to build.

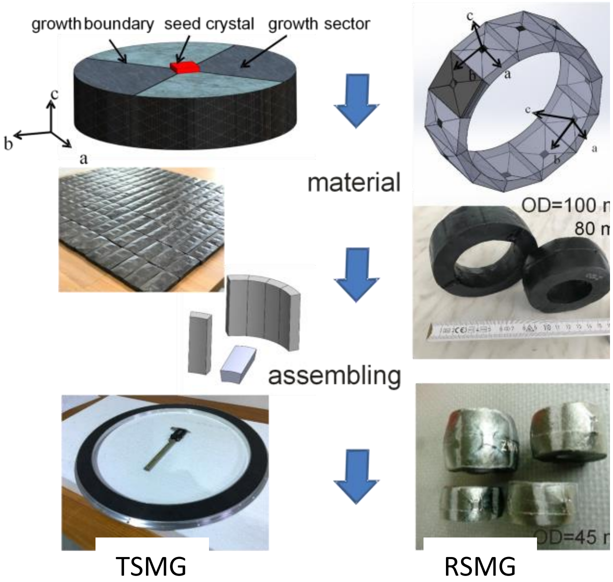

Figure 1. Comparison of standard top-seeded melt growth TSMG (a) and radial-seeded method RSMG (b)

Routinely multi-seeding fabrication is associated with a number of advantages relative to extremely large-crystal sample growing technique above 100 mm. Multi-seeding technique reduces the fabrication time even with including the necessary assembling. The multi-seed samples possess a higher mechanical stability compared to large grain bulks, and the fabrication reproducibility and material efficiency can be easier shifted into a pre-industrial level.

2.2 Top/bottom seeded YBCO bulks

In the standard TSGM or RSGM methods (Chapter 2.1) each quasi-crystal is grown epitaxial from one seed with higher melting route compared to the base material. Single grain samples show in most cases inhomogeneous trapped field distributions between top and bottom. The reason for that dependence is the Y123 decomposition process into Y211 and melt (in oxygen) and the following crystallization and growth of Y123 with Y diffusion through the melt. The longer the distance from the seed to the peritectic growing front the more difficult is the crystal grown. Hence, the bottom part compared to the top crystal is often less perfect crystallized.

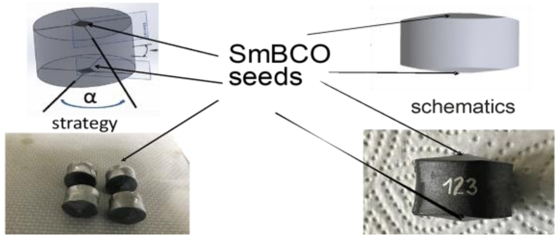

Figure 2. Melt textured top /bottom double seed configuration

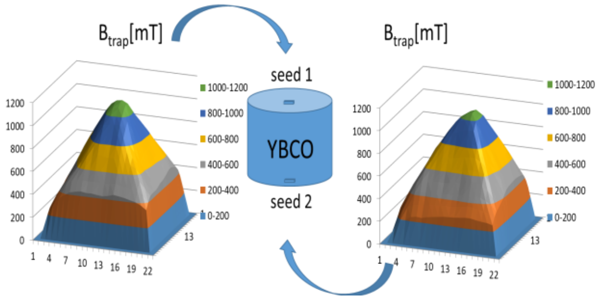

Figure 3. Top/bottom field mapping of a melt -textured 30 mm double-seeded YBCO sample.

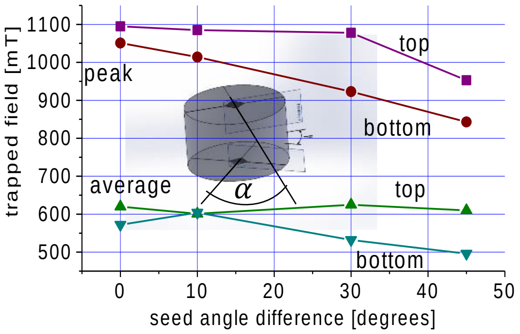

Figure 4. Flux density peak and average values of top/bottom measurements at double-seeded melt-textured YBCO sample.

Altogether four 30 mm YBCO samples are prepared, each with two seeds. They are melt-textured in a growing furnaces at the standard temperature route [4] and oxygenated at 400°C during 12 days. The fabricated samples are shown in figure 2. The azimuthal angle between top and bottom seed was varied from 0° to 45°, with the individual sample orientations (azimuthal angles) S1(0°), S2(10°), S3(30°), and S4(45°). Trapped field measurements of the field distribution from top and bottom of each sample, as it is displayed in figure. 3, show a systematic dependence on the seed mismatch angle α given in figure 2. At a magnetic excitation field of about 1.5 T the peak maximum extend from 1100 mT to 850 mT, while the averaged flux density spans from 630 mT to 490 mT. Both values are displayed in figure 4 as function of the seed angle difference, respectively. Maximum and averaged flux density of top and bottom are a function of the seed angle difference. The smaller the crystallographic mismatch angle α, the better the flux density ratio or homogeneity between top and bottom. On the other hand, at a large azimuthal angle difference α of 30° or 45° the two partial solidification fronts from top and bottom due to the large mismatch cannot fit into a congruent single crystal and show divergent flux density values (figure 4). The picture in the center of figure 4 shows the azimuthal mismatch angle. We can conclude that a top/bottom double seed configuration improves the electromagnetic bulk homogeneity whereby the relative top/bottom azimuthal seed orientation determines the final sample quality and homogeneity. The actual bulk thickness of 13 mm shows homogeneous electromagnetic properties from top to bottom according to the flux mapping results in figure 3. However, that behavior is surely dependent on the sample thickness, and presumably, a function of the sample diameter too.

2.3. High-field test: Bulk vs. ring

When using high external field-cooling above 5 T for excitation the electric and mechanical properties and their interaction basically limit the REBCO field trapping performance. Surprisingly, despite a greater number of careful experimental attempts accompanied by detailed numerical calculations [5] the obtained maximum trapped field values seem to level-off at about 12 T for single samples and about 18 T for mini-magnets. In addition, an experimental success in those levels could not be reproduced a second time at the same sample. The highest trapped field is obtained at a magnetic construct which consists of two stacked single REBCO disks. The trapped field is then measured between the stack. Additionally, for high-field excitation the REBCO samples are stabilized by metal ring encapsulation (stainless steel, Al alloy). Equally, the addition of Ag_2O to the precursors, like mechanical compression, should avoid mechanical fracture caused by the high Lorentz forces. The metal bandage, already at room temperature fitted is pre-compressing the sample and causes during cooling an additional compressive stress.

Especially critical is the stress propagation in REBCO ring-shaped samples. The stress concentration at the inner periphery is almost twice of that of the disk bulk. On the other hand, when solving the requested homogeneity a ring-shaped TFM is capable to act as promising magnetic device for NMR and MRI systems at competitive prices. In figures 5 and 6 we have been investigated the electromagnetic

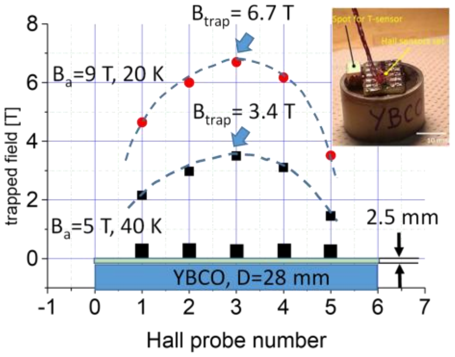

Figure 5. Field-cooling at 20 K and 40 K and mapping of a 28 mm melt-textured YBCO sample with 2 mm SUS316 ring.

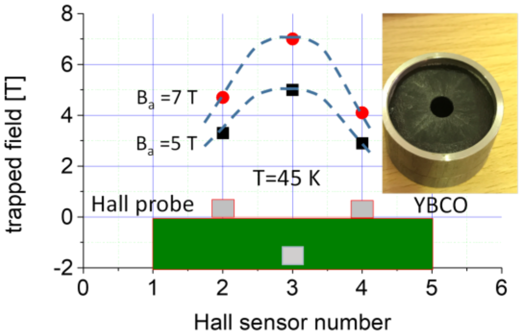

Figure 6. Trapped field results of melt textured YBCO ring stabilized by 2 mm SUS316 with 32 mm outer and 6 mm inner diameters.

behavior of a 30 mm bulk and a 30 mm ring at excitation values between 5-9 T and temperatures from 20 K to 45 K. Dependent on the positions of the Hall sensors (HGT 2101, Lake Shore, USA) on top in 2.5 mm distance in figure 5 and in the ring sample center in figure 6, the maximum trapped field shows a significant relation to the excitation field. While the Hall sensor in the ring sample center in figure 6 measures almost 100% of the external field B_a=5 T and 7 T, the Hall sensors 2.5 mm above the bulk surface in figure 5 display maximum trapped field values of 6.7 T at 9 T excitation (74% at 20 K) and 3.4 T at 5 T excitation (68% at 40 K). The distance of the Hall probe to the ring current determines the measured field. According to Ampere's and Biot-Savart's laws a ring current of the magnitude I encircling an area A produces at a distance large to its radius r, a magnetic field which is identical to that of a magnetic dipole of the moment $M= I \times A$. For the HTS bulks the magnetic performance B_{trap} is roughly determined by the critical current density J_c and the radius r where that current can flow.

3. Conclusion

For application-oriented YBCO material fabrication we have been demonstrated the successful variation of the seeding geometry to achieve hollow cylinder rings with radial *c* axes orientation. That fabrication strategy prevents expensive and sophisticated REBCO material machining and assembling. In parallel, top/bottom double seeding YBCO bulks give indications for a greater electromagnetic material homogeneity approaching NMR and MRI HTS bulk requirements. Finally, disk and ring bulk high field experiments at 5- 9 T show promising trapped field results at 20 – 45 K to gain practical robust TFM devices.

References

[1] Krabbes G Bieger W Schaetzle P and Wiesner U 1998 Improved HTSC bulk materials: a thermodynamic approach to processing *Supercond. Sci. Technol.* **11** 144–148.

[2] Gruss S, Fuchs G, Krabbes G, Verges P, Stover G, Muller K-H, Fink J and Schultz L 2001 Superconducting bulk magnets: very high trapped fields and cracking *Appl. Phys. Lett.* **79** 3131.

[3] Ikuta H 2003 High temperature Superconductivity Materials, ed. A.V. Narlikar (*Springer Verl. Berlin*) p.79 – 97.

[4] Werfel F N Floegel-Delor U Rothfeld R Riedel T Goebel B Wippich D and Schirrmeister P 2012 Superconductor bearings, Flywheels and Transportation *Supercond. Sc. Technol.* **24**, 014007.

[5] Ainslie M D Huang K Y Fujishiro H Chaddock J Takahashi K Namba S Cardwell D A Durrell J H 2019 Numerical modelling of mechanical stresses in bulk superconductor magnets with and without mechanical reinforcement *Supercond. Sc. Technol.* 2019, **32**, 034002.

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