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Materials Processing, Pulsed Field Magnetization and Field-Pole Application to Propulsion Motors on Gd123 Bulk Superconductors

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Abstract. Gd123 bulk superconductor is one of the promising magnet materials. We studied the materials processing to grow high performance magnet with a doping of nano-sized metal oxides such as ZrO₂ as a candidate of pinning centre. The enhancement of the critical current density was obtained. Growth of nano-sized particles of Gd₂₁₁ in addition to BaZrO₃ were observed by TEM. The formation of nano-sized particles appears a key to improve the integrated flux trapped inside the bulks and the TEM reveals an intriguing effect of the addition to the microstructure of bulk materials. Magnetization process is crucial especially for an extended machinery. Pulsed field magnetization was applied to the field-pole bulk on the rotor disk of the tested synchronous motor. The trapped flux density of 1.3 T for Gd123 bulk sample and of 60 mm diameter was reached in the limited dimension of the tested motor by a step cooling method down to 38 K with a closed-cycle condensed neon. The pulsed magnetic field was applied with a new type of split-armature coil. A large bulk of 140 mm diameter has also shown a potential flux trapping superior to other smaller specimens. The bulk magnet provides a strong magnetic field around the bulk body itself with high current density relative to a coil winding. A comparative drawing of a “torque density” of a variety of motors which is defined as the torque divided by the volume of the motor indicates a potential advantage of bulk motor as a super permanent magnet motor.

1. Introduction
Potential application of melt-growth high-temperature bulk superconductor (HTS) is reviewed from the viewpoints of materials processing, pulsed magnetization and application to the rotating machines. The bulk HTS provides a large magnetic density flux with a large gradient of the flux density around the bulk. For example, when we attempt to form a magnetic field up to 1 T by using a HTS winding, it
is necessary to wind a HTS coil with at least 160 mm in diameter as a double pancake and cool down to around 30 K to apply a large current density without generating a heat. In this respect, the melt-growth bulk materials provide a dense flux of magnetic field more than 1 T after the magnetizing materials with 30 mm diameter and 20mm thickness for example. Therefore, it is quite natural to design a variety of machines with a bulk magnet in place of the conventional permanent magnet [1]. For successful commercialization of HTS bulk machines, we have to improve and fix the following terms. Firstly, enhancement of the critical current density under the magnetic field by introducing a new material process with respect to the function of flux pinning. Secondly, the improvement of the magnetization process, crucial for advanced machinery. A conventional field cooling magnetization with a separate superconducting magnet provides an extremely high intense magnetic flux up to 17 T [2]. However, for mobile use and on-site magnetization as well as magnetization of field pole of rotating machines, it is necessary to magnetize by applying a pulsed magnetic field after cooling inside the machines or under other equivalent situations [3]. We have to find an optimized geometry as well as optimized pulsed coils to be used in the machines. Thirdly, to excite the bulk magnet inside the machines, one has to do effective cooling without excess loss by using a compact machine with reducing both dimension and weight [4]. In this paper, we report our recent progress on the above mentioned three subjects. We observed inhomogeneous distribution of second phase particles by scanning electron microscopy and higher superconductivity in nanoparticles ZrO$_2$/ SnO$_2$ doped GdBa$_2$Cu$_3$O$_{7-\delta}$(Gd123) bulk superconductors.

2. Materials processing of Gd123 bulk HTS

In recent years, the nano sized precipitates inside bulk superconductors or directly doping nanosized particles in the bulk have attracted much attention in the efforts to obtain more effective pinning and higher superconductivity [5,6]. Commercially available, Gd$_2$O$_3$ (3 N), BaO$_2$ (3 N) and CuO (3 N) powders were used to prepare Gd211 particles. The mixed powders were annealed in air at 900 °C for 20 hours. The average size of as-grown Gd211 was around 1 µm. Commercial powder GdBa$_2$Cu$_3$O$_{7-\delta}$ (3 N, Gd123) and as-grown Gd211 were weighed in a nominal molar ratio of 10 : 3 and mixed thoroughly together with SnO$_2$ or ZrO$_2$ powders, both with average particle size of 50 nm. The melt-process of bulk superconductors of 24 mm diameter and the post annealing in argon and oxygen gases have been reported elsewhere [7]. A small air-processed Nd123 crystal with a melt point of 1057 °C in air was used as seed for each bulk. Superconducting properties were measured with a Quantum Design SQUID magnetometer. The highest $J_c$ at liquid nitrogen temperature for each composition is 68,000 A/cm$^2$; 100,000 A/cm$^2$ and 80,400 A/cm$^2$ in 0.004 ZnO; 0.004 ZrO$_2$ and 0.008 SnO$_2$, respectively.

Figure 1(a) shows a TEM photograph of Gd123 bulk with nanosized ZrO$_2$ addition. Compared to the Gd123 bulk without nanosized particles addition, there are many small particles with the sizes less than 100 nm. Compositional analysis by x-ray energy dispersion spectrum (EDS) shows that these particles are sorted into two kinds, Gd211 nanoparticles about 100 nm and BaZrO$_3$ nanoparticles less than 50 nm (right inset of fig. 1(a)). Chemical reactions between ZrO$_2$ nanoparticles and Gd123 phase investigated with x-ray diffraction and differential thermal analysis show that ZrO$_2$ addition almost totally changes into BaZrO$_3$ phase at around 940 °C, a temperature well below the growth window for partial molten processing. It is the reason why we never find ZrO$_2$ particles inside the Gd123 bulk but only BaZrO$_3$ particles, which keep a nano-size as shown right inset of fig. 1(a). This also indicates that BaZrO$_3$ nanoparticles do not coarsen during the crystallization of Gd123 single domain. The smaller size and the stable properties of the BaZrO$_3$ make it an effective pinning centre of the bulk, which contributes to the enhancement of the $J_c$ of the bulk.

It is well known that the nanosized particles doping can cause more faults, which can affect the microstructure of the bulk. Figure 1(b) shows the TEM image of the micro-defects together with Gd211 and BaSnO$_3$ small particles of the Gd123 sample with 0.8 mol % SnO$_2$ addition.
Figure 1. TEM photographs of Gd123 bulk with nanosized ZrO$_2$ addition. Inset shows the BaZrO$_3$ particles (a), TEM image of the micro-defects together with Gd211 and BaSnO$_3$ small particles of the Gd123 sample with 0.8 mol % SnO$_2$ addition (b).

Similarity to the ZrO$_2$ doped sample, small BaSnO$_3$ particles are also observed into the SnO$_2$ doped Gd123 bulk superconductors. Micro-defects, especially twin structures are observed, the average width of the twinning is about 100 nm. Moreover, both dislocations and stacking faults are observed in the twinning plane. These defects are mostly small sized and play the role of pinning centres to enhance the superconducting properties in the present studies. They are the origin of the enhancement of critical current density $J_c$ in the nanosized particles doped bulk [8].

3. Magnetization by using a split-type vortex coil with a pulsed-current for Gd123 bulk

Pulsed-field magnetization (PFM) is a promising technique to put an intense magnetic flux inside the superconductor bulk at low temperature. It is very convenient to magnetize the bulk pellets upon operating the machines by using a copper coil with a pulsed current. The task to be solved is how to apply the pulsed magnetic field to obtain a high intense magnetic flux pinned inside the bulk. This kind of study has to pay attention to a magnetization dimension i.e., the size of the bulk vs. applied magnetic flux geometry and temperature [9].

We have applied the PFM for the large Gd123 bulk with 140 mm diameter and 20 mm thickness by using a pulsed copper vortex coil with 140 mm diameter. The present copper windings is in two parts to play two roles: full dimension of 140 mm diameter and a partial dimension of 100 mm diameter. A copper wire with $\phi$ 2 mm was used and the pulsed current was applied by a hand made current generator. This coil was named as a CMDC, controlled magnetic field density coil [9]. One can make a sequence of combination of the generation of magnetic field using either $\phi$140 mm or $\phi$100 mm part. The bulk specimen was inserted between two layered stack of CMDC and was immersed into liquid nitrogen. Figure 2 exhibits the obtained magnetic field density measured on the plane 4 mm above the surface of the bulk after field cooling (a) as well as a view of the Gd123 bulk sample (b). The result of figure 2(a) was obtained by a conventional field cooling under 4 T at 77 K using a superconducting magnet.

Figure 2(c) shows a trapped magnetic flux obtained by successive pulsed magnetizations using a CMDC with a $\phi$ 100 mm effective diameter of applied current which is mostly equivalent to the size of an applied magnetic flux smaller than the diameter of the bulk. By the present result, the pulsed magnetization process is caused by an induction current on the surface of the bulk coming from the applied pulsed magnetic field as a function of time.
Figure 2. Trapped magnetic flux obtained in the plane at 4 mm above the surface of the 140 mm bulk by using a conventional field cool magnetization (a), the photo of the Gd123 bulk of 140 mm diameter [10] (b), the trapped magnetic flux upon a weak pulsed magnetization with a CMDC of 100 mm diameter (c).

Figure 3. Trapped field density profile along the growth sector zone of the Gd123 bulk with $\phi = 60$ mm by using two step PFM at 55 K and 38 K with a CMDC: full dimension of 84 mm diameter and a partial dimension of 44 mm diameter [11] (a), the bulk HTS motor coupled with a GM cryocooler. Figure 3(a) shows the trapped magnetic flux at different positions 1 mm above the surface of Gd123 bulk with a 60 mm diameter and a 20 mm thickness with a sequence from PFM using $\phi$ 84 mm CMDC at 55 K, $\phi$ 44 mm CMDC at 55 K, $\phi$ 44 mm CMDC at 38 K and $\phi$ 44 mm CMDC at 38 K. The maximized flux density was 1.3 T. The multiple PFM were carried out in the bulk HTS motor coupled with a GM cryocooler. The weight of the bulk HTS motor is around 200 kg for the target specification of 90 kW, 720 rpm.
4. Potential application of Gd123 bulk to a compact, light weight and high torque density motor

The HTS motor has been intensively studied in several countries with respect to electric ships, wind power generations, and condensers, etc. The most important schema is reducing the heat generated from the HTS part as far as we have to cool down the temperature of the HTS magnet part. We have to avoid the use of liquid cryogen to cool down and to immerse the HTS part because the liquid has to be supplied continuously with a substantial electric power. The conduction cooling associated with a closed-cycle gas circulation assisted with a cryocooler is a better choice. Secondly, the weight has to be much lighter than a comparable conventional motor such as induction motor. We have employed a bulk HTS as field pole magnets on the rotor of the axial-type motor [12,13]. With a small dimension of φ 600 mm x 500 mm and light weight around 200 kg, the target specification is 90 kW with 720 rpm as proposed in 2005 and shown in fig. 4(a). In the present stage, 48 kW, 720 rpm were estimated during the successful operation of twin rotor operation with 16 pole field magnets [14] as shown in fig. 4(b).

The progress of the bulk HTS motor has much potential application to exceptionally light weight propulsion motor not only for ships but also any other vehicles coming from iron-less without back iron in contrast to other products by using a HTS windings. The key technology remaining pulsed field magnetization and optimization of control of armature current flow on core-less armature windings. In our design, the armature windings can be also cooled down by using a cryogen separated from the field-pole cooling system.

![Figure 4. A photograph of a HTS bulk motor coupled with a GM cryocooler (a), torque density of the rotating machines for ship propulsion for both conventional and HTS motors(b). Bulk-M2 and Bulk-M3 indicates two models constructed in our group. In the motor signed as Bulk-M3, three rotors with 24 pole-field bulk magnets can be installed in the frame. 8 pole-field bulk magnets on the rotor plate are cooled down by a circulating cryogen inside the rotor.](image)

5. Summary

We studied the materials processing of Gd123 bulk magnet with a doping of nano-sized metal oxides such as ZrO$_2$ as pinning centres. The enhancement of the critical current density was obtained up to 100,000 A/cm$^2$. Growth of nano-sized particles of Gd211 in addition to BaZrO$_3$ were observed by TEM. The formation of nano-sized particles is shown to be a key for improving the integrated flux trapped inside the bulks. The TEM reveals an intriguing effect of the addition to the microstructures of bulk materials.

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