Compactly Composed Strong Magnetic Field Generators with Cryo-cooled High Temperature Bulk Superconductors as Quasi-Permanent Magnets

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Abstract. The authors have constructed various types of strong magnetic field generators using superconducting bulk magnets in conjunction with compact refrigerators. The magnetic field in the open space outside the vacuum chamber that contains a bulk magnet has been estimated as over 3 T when activated by the static fields of a 5 T superconducting solenoid magnet. The authors have tried to extend the variation of such strong field generators which are promised to develop in the future. In the study, a novel and compact bulk magnet system with use of a compact pulse tube cryocooler has recorded the maximum trapped field of 2.78 T on the magnetic pole surface. The characteristic feature of superconducting bulk magnet is defined as a compact and strong magnetic field generator. This implies that various kinds of equipments must be successively proposed even in the very early stage of industrialization of strong magnetic field generators.

1. Introduction

It is well known that the melt-processed REBa2Cu3Oy (RE=Y, Sm, Gd, Dy, Eu; abbreviated as RE123) bulk materials bearing RE2BaCuO5 (RE211) fine particles act as quasi permanent magnets when they trap the applied magnetic field [1, 2]. The performance of bulk superconducting bulk magnets has been greatly improved by fabricating large and homogeneous material, that exhibit single domain distributions in the magnetic field mapping [3]. The developments of production processes have led stable supply of bulk materials in the commercial market.

Meanwhile, M Tomita and M Murakami [4] have pointed that it is quite important to reinforce the materials to prevent the fracture due to the magnetic forces applied during the magnetization processes. The fracture of bulk material has been reported by Y Ren et al [5]. That happens when they capture the intense magnetic field of around 8 T.

The authors have been emphasizing the importance of adopting refrigerators to keep the superconductivity instead of using cryogen such as liquid nitrogen, since the handling of cryogen requires us complicated skills and does not fit for the widespread industries. In addition, we know that it is much effective to use the materials in the temperature range lower than 77 K where the superconducting properties greatly enhance [6]. As is reported by H Ikuta et al [7], the maximum trapped field rises up to 9 T at 25 K, which is more than 5 times as strong as that of 77 K. The recent data reported by G Krabbes et al [6] and M Tomita et al [4] have clearly shown the excellent trapping abilities of 16.0 T at 24 K and 17.24 T at 29 K, respectively.
The authors have constructed various types of novel magnetic field generators with various kinds of sizes and shapes of magnetic field [8]. Furthermore, the attempts toward the practical industrialization of intense magnetic fields have been referred in several technologies [9].

As shown in figure 1, the positions in the practical market of the trapped field magnets among other field generators have been presented from the industrial point of view. The superconducting bulk magnet is characterized by its compactness and strong fields. A number of R&D projects heading for the practical applications have already started to realize the prosperous industries. In the paper, recent topics are reported on the construction of superconducting permanent magnet system with use of a compact cryocooler.

2. Experimental procedures

2.1. Melt-processed RE-Ba-Cu-O bulk materials

Figure 2 shows a typical RE-Ba-Cu-O bulk magnet (RE=Gd) which was manufactured by Dowa Mining Co., and it was adapted to our experiments. The dimensions are 60 mm in diameter and 15 mm in thickness. A trace of a seed crystal at the centre and the grain growth sector boundaries on the surface are characteristic features of magnetically single domain bulk materials and this makeup suggests the high field trapping ability after magnetic activation treatments. As shown in the figure, the sample was reinforced by putting a stainless steel ring on to stand the stress due to the magnetic force and thermal shock during the magnetizing procedure conducted by field cooling method in which the strong magnetic field of over 5 T is applied by using the superconducting solenoid magnet. The bulk magnet shown in the figure was actually installed to the compact bulk magnet system composed by the ST pulse tube cryocooler which are referred below in comparison with a GM cryocooler.

2.2. Compact cryocoolers

Figure 1. Positions of HTS bulk magnets among various types of magnetic field generators.

Figure 2. Gd 123 superconducting bulk magnet reinforced by stainless steel ring.
Figures 3 shows a Gifford-McMahon (GM) cycle cryocooler (type GR101) and a Stirling (ST) cycle pulse tube cryocooler manufactured by AISIN SEIKI Co., which enable us to get the nominal temperatures of 35 and 50 K, respectively. GM refrigerator (figure 3(a)) is connected to a compressor by a couple of flexible tubes through which helium gas transfers for heat exchange. On the other hand as shown in figure 3(b), a compact ST pulse tube cryocooler includes a couple of compressors driven by the voice-coil type motors which synchronize to reduce the vibration. It is constructed to be a smaller system than GM cryocooler in size. The nominal output and input powers have been reported as 15 W and 1,000 W for GM cooler, and 8 W and 300 W for ST pulse tube cooler at 77 K, respectively. As listed in table 1 below, the common characteristic features are compactness and high durability with a long interval between the inspections to maintain them.

2.3. Activation and trapped field measurement
In this study, field cooling (FC) magnetizing technique was conducted to realize high field trapping. The process was operated by a superconducting solenoid magnet which was directly cooled by a GM cryocooler without using liquid helium, which was manufactured by Japan Superconductor Technology Co.

The trapped field distribution after the FC process was measured by scanning an axial-type Hall sensor (F. W. Bell, BHA921) just above the vacuum chamber with a gap of 0.5 mm and feeding current of 100 mA to the sensor. The direction of thus measured magnetic field was parallel to the bulk sample axis. The sensor intermittently scanned with a 2 mm pitch and an interval of 1 s. The distance between the sensor and the bulk surface was designed as 3.5 mm.
3. Results and Discussions

3.1. Strong magnetic field generators

Y Yanagi et al [10] reported that the superconducting magnet system trapped the maximum field of 6 T in the open space outside the vacuum chamber after the activation by FC method using the static field of 8.5 T generated by a superconducting solenoid magnet. It is necessary to obtain more compact devices than those above to apply the bulk magnets to the widespread industries.

Figure 4 shows a structure of newly developed compact magnet system consist of ST pulse tube cryocooler shown in figure 3 (b). The heat exhausts through the copper conduction rods connected from the cold head to the bulk stage. The copper rods are thermally insulated from outside the chamber with use of a FRP supporting tube which sustains the rod between cryo-cooled bulk stage and the vacuum chamber of the room temperature. Figure 6 shows a photograph of the whole system constructed by an ST pulse tube cryocooler. The cryocooler is directly attached to the vacuum chamber and a whole system can be placed on an ordinary table, since the whole weight is designed to be lighter than 20 kg. As shown in figure 6, the temperatures of bulk sample stage and cold head of the cooler reached the ultimate temperatures of 59 K and 54 K from the room temperature in about 8 hours, respectively.

3.2. Magnetic field distribution

In the FC process shown in figure 7, the magnetic pole was inserted into the room temperature bore of the superconducting solenoid magnet. A static field of 5 T was applied in the higher temperature range than $T_c$, and then the sample was cooled to the ultimate temperature of the cooler. After that, the applied field was reduced to zero with a descending rate of 4.2 mT/s to control the heat generation due to the flux motion in the sample. Actually, the temperature rise during the process was carefully repressed less than 1 K.
Figure 8 shows the trapped field distribution map which was measured for $B_z$ in the open space outside the vacuum chamber. No-strain single cone shape makes it sure that the sample has no serious weak links in it. The maximum trapped field has reached 2.78 T at the very centre of the ferromagnetic pole surface. The magnetic field along the axis of the bulk magnet is plotted against distance from the vacuum chamber surface in figure 9. As shown in the figure, the maximum trapped field reached 2.78 T at the surface of the vessel, and the data was extrapolated to be 3.55 T at the surface of the bulk superconductor. The specifications of the bulk magnet systems using GM and ST pulse tube coolers are listed in table 1. The generating magnetic fields outside the vacuum chambers have exceeded the performances of large scale electromagnets and permanent magnets by the rare earth element which is capable of emitting 2 T and 1 T, respectively. As shown in figure 1, the industrial position of bulk magnet system lies in the superior region to that of electromagnets, which is a novel area with respect to the magnetic field generators, and is characterized as a more compact and less expensive device than conventional superconducting magnets and a stronger field generator than the permanent magnets.

4. Conclusions
A compact magnetic field generator has been newly constructed with use of a compact ST pulse tube cryocooler to expand its application area to the widespread industries. The magnetic performance has reached 2.78 T in the open space outside the chamber when magnetized in static field of 5 T by FC method. Various kinds of superconducting bulk magnet systems capable of generating strong magnetic fields have been developed by adopting compact refrigerators and magnetizing operations.

**Table 1. Major specifications of magnetic field generators using cryo-coolers**

| Cooler type         | GM cycle cooler | ST pulse tube cooler |
|---------------------|-----------------|---------------------|
| Generating Field    | 3.37 T          | 2.78 T              |
| Activation          | Field cooled at 30.8 K | Field cooled at 62.0 K |
| Output power at 77 K| 15 W            | 8 W                 |
| Input power         | 1,000 W         | 300 W               |
| Maintenance interval| 5,000 h         | 30,000 h            |
| Weight              | 80 kg           | 18 kg               |

The field was measured at the surface of magnetic pole in the open space.
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