Improvement of trapped magnetic field in GdBCO by waveform control pulse magnetization at 70 K

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Abstract. We attempted to trap a strong magnetic field with a single pulsed magnetic field by applying waveform control pulse magnetization (WCPM) method to a high-temperature superconductor (HTS) bulk sandwiched between two vortex-type copper coils at less than 77 K. The GM cryocooler conductively cooled the GdBCO bulk to 70 K in an arrangement similar to the internal structure of our axial gap type HTS motor. The HTS bulk showed no flux jump, while the duty ratio of WCPM was small. When we increased the duty ratio, we found a flux jump without looking at any prior signs and the trapped magnetic flux density increased twice. Hence we attempted a negative feedback WCPM with the control target at the highest trapped magnetic flux density while no flux jump was found. After trial and error of control conditions, the HTS bulk sample trapped a maximum magnetic flux density of 1.79 T by a single pulse magnetic field. If the WCPM technique is used, a single pulse magnetic field will cause the HTS bulk to obtain a higher trapped field at lower temperatures.

1. Introduction

Most of the energy produced in the world is generated by rotating machinery. And about half of the energy is consumed by motors. In recent years, the opportunity to replace an internal combustion engine with an electric drive engine has increased, and there is a need to develop more efficient electrical rotating machine systems. We have developed motors using high-temperature superconductor (HTS) bulk materials to realize such rotating machines [1]. HTS motors, which can replace traditional motors smaller, lighter and more efficiently, will be used for future ship and aircraft propulsion, and renewable energy generators [2, 3].

Since about 20 years ago, practical permanent magnet motors have been developed, and research using HTS bulk materials is also progressing [1, 2, 4]. HTS bulk materials can trap strong magnetic field, but for that we need to generate strong magnetic field using a superconducting magnet [5, 6]. In general, a superconducting magnets for magnetizing HTS bulk materials are large, heavy, and expensive, so it is difficult they are used to magnetize HTS bulk for field poles built into rotating machines with complex structures and small internal spaces. Although pulse field magnetization (PFM) can realize a relatively simple and inexpensive system, improvement of the trapping magnetic field characteristic is a problem [7]. By local heat generation due to dynamic transient flux flow when applying a strong pulsed magnetic field, the trapped flux density distribution can be asymmetrically distorted and less than the trapped magnetic
flux density by field cooling (FC) magnetization [8, 9]. Until now the various magnetization techniques have been tried to improve the suppression characteristics due to transient heat from flux motion [10–12].

2. Pulse field magnetization technique

In conventional PFM, a magnetizing power supply applies a pulsed high magnetic field to the HTS bulk. The high magnetic field has a sharp rise and a fast relaxation time due to the electrical constants of the device. The behavior of the pulsed high magnetic field of rapid rise and fast relaxation time is determined by the electrical constant of a magnetizing power supply, but not to facilitate the HTS bulk magnetization. The waveform control pulse magnetization (WCPM) method is a technology that enables the HTS bulk to easily trap a magnetic field by applying a PWM-controlled pulsed magnetic field [13]. In order to apply a strong magnetic field to the bulk, the pulse magnetizing power supply causes a large current to flow through a coil with a large self-inductance. When the pulse current is suddenly cut off, the counter electromotive force generated in the magnetizing coil due to the chopping of the current reflows through the flywheel diode, and the pulse current gradually decreases. Therefore, by repeating the chopping of the pulse current in a short time, we can deform the pulse magnetic field waveform to some extent. If the magnetizer generates and applies a pulsed magnetic field waveform suitable for the bulk, we can trap a strong magnetic field. Duty ratio \( D = t_H/(t_H + t_L) \) of chopper control determines the rate of change. In order to continue to use the pulse magnetizer safely, we set \( t_H + t_L \) as the period to 1 ms. We made a magnetizer to realize such PFM in Ref. [14]. In the past, we have tried WCPM with sequential PWM control and feedback PWM control. Especially, the method that improved the trapped magnetic field characteristics the most was the negative feedback PWM control using the magnetic flux density that intruded the HTS bulk during PFM [13]. The magnetic field negative feedback waveform control pulse magnetizer we made has the configuration shown in Ref. [13]. The Hall voltage measured on the surface of the HTS bulk while applying the pulsed magnetic field is sent to the microcontroller (MCU) via

Figure 1. Bulk sample geometry for pulse field magnetization and measurement.
Figure 2. Results of conventional PFM. (a) Pulse current waveform corresponding to 12.3 kJ, and (b) trapped magnetic flux density obtained for each pulse magnetization energy.

A 16-bit analog-to-digital converter (ADC), and this information about magnetic flux density is used to determine the duty ratio \( D \) by using PID control. Immediate change of duty ratio by negative feedback from the Hall element at the center of bulk surface strongly magnetized the GdBCO bulk. From recent research, it is clear that flux jump is greatly related to the trapped magnetic field characteristics in pulse magnetization \([15, 16]\). A single pulse magnetic field achieved a maximum trapped magnetic field of up to 1.63 T which corresponds to 96% of magnetization by field cooling (FC) at 77 K when we tried to control the flux jump generation based on our experimental results of sequential WCPM.

The HTS motor should effectively use the strong magnetic field generated by the HTS bulk. Consequently, the HTS bulk in a practical motor must be cooled well below the liquid nitrogen temperature of 77 K in our study. So far, we had magnetized with WCPM by immersing the HTS bulk and coils in liquid nitrogen. Only recently was a new magnetizer available, accordingly we had attempted WCPM experiments on a GdBCO bulk at temperatures below 77 K and aimed to trap strong magnetic fields with a single pulsed magnetic field.

Figure 1 shows the configuration near the sample holder of the low-temperature pulse magnetizer manufactured for the WCPM experiment. In order to make it easy to operate with HTS bulk samples, our magnetizers are arranged upside down. The structure in which the bulk sample is sandwiched between two vortex-type copper coils suits the internal structure of our axial gap type HTS motor \([2]\). The magnetizing coil is similar in shape to that used in the armature shown in Ref. \([2]\). The self-inductance of the two vortex-type coils connected in series is 1.28 mH. Since the HTS bulk and the magnetized coils are separated from the cold head, the pulsed magnetic field does not affect the operation of the cryocooler. In addition, almost no stress generated during pulse magnetization is applied to the cryocooler through the thermal conductor. The bulk sample was GdBCO (GdBa\(_2\)Cu\(_3\)O\(_{6.9}\) 70.9 wt%, Gd\(_2\)BaCuO\(_5\) 19.2 wt %, Ag 9.4 wt%, Pt 0.5 wt %, QMG, Nippon Steel Corp.) with a diameter of 45 mm and a thickness of 19 mm, and 1.7 T was trapped by FC at 77 T. We fixed the HTS bulk and the magnetic coils sample 5 mm apart, and placed 5 Hall elements at the center, growth sector (GS) and growth sector boundary (GSB) on the bulk surface of the front side to measure the magnetic flux density. In order to trap the magnetic flux density for the negative feedback WCPM, a Hall element was attached to the center of the backside, and Cernox sensors for temperature measurement were attached. Mounting the Hall element for the negative feedback WCPM on the back side is not a problem as long as it is not affected by the HTS bulk crystallinity because a magnetic field
Figure 3. Increasing trapped magnetic flux density due to flux jump around 1.9 T during sequential waveform control. It was measured at the (a) Center (b) GS region on the HTS bulk surface for each duty ratio.

Table 1. Trapped magnetic field by the sequential WCPM of 12.3 kJ at 70 K.

| D [%] | $B_{T_{max}}$ [T] | Flux jump |
|-------|-------------------|-----------|
| 40    | 0.70              | Occurred  |
| 35    | 0.34              | None      |
| 30    | 0.29              | None      |

distribution generally uniform is maintained between two adjacent vortex-type coils.

3. Experiment and result
At first in this study, we measured the magnetic flux density HTS trapped in a bulk material cooled to 70 K by conventional PFM with an LCR transient response. The pulse current waveform obtained during conventional pulse magnetization is shown in the figure 2(a). Compared to the current at 77 K shown in Ref. [17], the pulse width was reduced by approximately half because the change from liquid nitrogen immersion cooling to conduction cooling by the GM cryocooler affected the magnetizing coils. Figure 2(b) shows the trapped magnetic flux density obtained for each magnetizing energy. As the magnetizing energy increases, the respective trapped magnetic flux densities decrease. Especially, the magnetic flux trapped by the GS region decreases greatly as the energy increases. This result may be because the magnetic flux motion may be easily caused in GS with few pinning centers while the magnetization energy is large.

In the next experiments, we investigated how the magnetic flux density captured by the HTS bulk is improved by WCPM, when a relatively high magnetization energy of 12.3 kJ is applied. During sequential WCPM with a fixed duty ratio $D$, the smaller $D$, the pulse width becomes wide with a slow rise of the applied pulsed magnetic field. On the other hand, the larger $D$, the pulse width is narrowed and as the pulse rises sharply. And if $D = 100\%$, a conventional pulse waveform is generated. Sequential WCPM with constant $D$ caused flux jump in HTS bulk with $D \geq 40\%$. This is shown in the figure 4 and table 1. The flux jump greatly improved the trapped magnetic field of the HTS bulk, and the maximum trapped magnetic flux density was doubled. The plots of the penetrated magnetic flux density distributions at the center and GS region of the HTS bulk where magnetic flux easily moves indicate that the HTS bulk suppressed the flux
jump near 1.9 T, and increased the magnetic flux density when it could not be suppressed. This result suggests that the boundary of the magnetic flux density causing the flux jump exists in the vicinity of 1.9 T.

Therefore, we tried a negative feedback WCPM with a magnetic flux density slightly higher than 1.9 T set as the target value, similar to the experiment at 77 K. While the target magnetic flux density $B_{\text{target}}$ was low, the HTS bulk did not cause flux jump as shown in figure 4(a) and the trapped magnetic field was very small. As $B_{\text{target}}$ increased, we found a flux jump at $B_{\text{target}} \geq 2$ T. At this time, the magnetizer should have tried to suppress the flux jump. The impulses that often appear in the figure 4 look like electrical noise, but may indicate that the flux jumps have been suppressed. The relationship between this impulse and the trapping magnetic field is not clear here, but in any case the maximum trapped magnetic flux density $B_T$ in there increased to about 5 times with the occurrence of flux jump. When the $B_{\text{target}}$ value was adjusted and the single pulse magnetization was repeated, we finally obtained $B_T = 1.79$ T as shown in figure 5. This is a magnetic flux density that is more than 4 times larger than the

Figure 4. Conditions for improving flux density measured at the (a) Center (b) GS region (c) GSB region on the HTS bulk surface for each control target magnetic flux density.
conventional PFM $B_T = 0.418$ T shown in figure 2(b) for the magnetization energy $E = 12.3$ kJ. Despite the increased energy loss in the coil due to the change to conduction cooling, the almost maximization of the trapped magnetic field as before indicates the effectiveness of this WCPM. Furthermore, it is the largest $B_T$ at the present time brought about by a single pulse magnetization using WCPM.

4. Conclusion
We tried the waveform controlled pulse magnetization at a temperature lower than 77 K for the GdBCO bulk material for the first time and obtained experimental result at 70 K. A condition for magnetic flux jump was found in a single pulse magnetization experiment with a different duty ratio. The trapped magnetic field was observed to increase rapidly due to flux jumps at the bulk center and GSB region when the applied magnetic field was controlled by the negative feedback the state of magnetic flux penetration in the bulk. The maximum trapped magnetic flux density we have obtained from the experiment is 1.79 T. This result, which has been reproduced, is the highest trapped magnetic flux density achieved in single pulse magnetization to date for GdBCO at 70 K. The new structure we have created to cool the HTS bulk to low temperatures works fine, and experimental results show the possibility of obtaining a high trapped magnetic field with WCPM even when the HTS bulk is cooler.

Also, since it has been confirmed that the trapped magnetic flux density starts to decrease as the time occupying the strong magnetic field region becomes longer, the control of this time may be related to the improvement of the trapped magnetic field characteristics along with flux jump. From now on, it is necessary to pay attention to the relationship between the strong magnetic field occupation time and the trapped magnetic flux density. In the next step, by attempting WCPM at lower temperatures, we will obtain a higher maximum trapped magnetic flux density from a single pulsed magnetic field.

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