

Study on methods to suppress decay of trapped magnetic field in HTS bulk subjected to AC magnetic field

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It was found in our previous experiment that trapped magnetic field in high temperature superconductor (HTS) bulks are decayed when the bulks are subjected to perturbation of magnetic fields. This phenomenon is inconvenient for the applications of HTS bulks and it is necessary to develop methods to suppress the decay. It was proven also in our previous experiments that the decay is caused by temperature rises of the bulks due to AC losses in the bulks. In the paper, studies on mechanism of the decay are reviewed. Methods to suppress the decay are proposed based on those studies and their effectiveness is experimentally investigated.

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1. Introduction

Technology of high temperature superconductor (HTS) bulks has made great progress in recent years and bulks producing more than 2 T at 77 K and 10 T at 20 K have been developed. This progress makes various applications realistic. Especially, compact and highly efficient electric motors and actuators, and non-contact bearings for flywheel energy storage systems are most promising applications [1]~[3].

The HTS bulks in these applications are exposed to magnetic field perturbation. The perturbation causes AC losses in the bulks and decay of the magnetic field trapped in the bulk. Theoretically, according to the Bean model [4], the reduction of the trapped field does not depend on the frequency of the external magnetic field. The trapped field is decreased at the first cycle of the AC external magnetic field by the amplitude of the external field and, after this first reduction, the trapped field is unchanged. However, we found in a previous experiment that amount of the reduction of the trapped field was dependent on the frequency of the AC external field and that the trapped field was kept decreasing even to zero during the application of the relatively high external field as shown in Fig. 1 [5]. This result is different from that is theoretically predicted from the simple Bean model.

From the stand point of the applications, decay of the trapped magnetic field is inconvenient and methods to suppress the decay need to develop.

To study on methods to suppress the decay, it is necessary to understand reasons for the decay of the trapped magnetic flux. In the previous studies, it was found that the AC losses in the bulks due to perturbation of the external magnetic field caused the decay [6]. When AC magnetic field is applied to a superconductor bulk, AC

losses are generated in the bulk. These AC losses raise the temperature of the bulk. This temperature rise decreases the critical current density J_c of the bulk. The reduction of the critical current increases the AC losses more and decreases the trapped magnetic field. Therefore, to suppress the decay of the trapped magnetic field, it is necessary to suppress the temperature rise of the bulk.

In this work, methods to suppress the decay are proposed and effectiveness of the proposed methods is experimentally investigated.

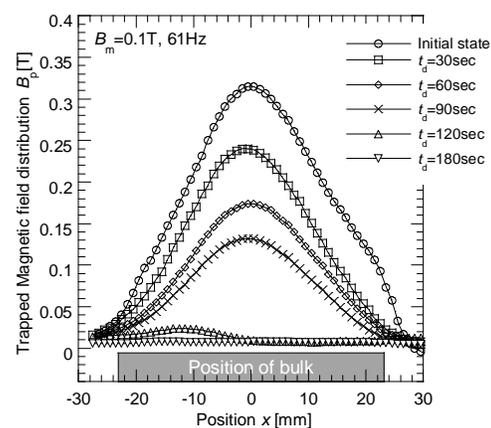


Fig. 1. Magnetic field distribution along the line on the bulk center dependent on the duration of the AC magnetic field application. Dimensions of the bulk are $\phi 46\text{mm}$ and 21mm thick. B_m : The amplitude of the external AC magnetic field. t_d : Duration of the external AC magnetic field.

2. Theory of decay of trapped magnetic field

2.1 Behavior of trapped magnetic field

Behavior of the trapped magnetic field in a HTS bulk subject to external AC magnetic field can be explained by the Bean model. The bulk is assumed to be a cylinder of infinite length for the simplicity of the analysis. Fig. 2 shows distributions of the trapped magnetic field B and current density J in a HTS cylinder of radius r_0 subject to AC magnetic field of amplitude B_m parallel to the cylinder axis. J_c is the critical current density of the bulk that is dependent on the bulk temperature T . Fig. 2 is for the case that B_m is lower than the peak of the initial trapped magnetic field B_{p0} . In the initial state, the magnetic field is trapped in the bulk by the superconducting current as shown in Fig. 2 (a). The external magnetic field starts to penetrate into the cylinder from the surface, and shielding current whose density is J_c is induced in the bulk. At the end of one cycle application of the AC external magnetic field, the peak of the trapped magnetic field is reduced by the magnitude B_m and the shielding current induced by the external field is hold in the bulk as shown in Fig. 2 (b). If the temperature of the bulk and J_c are not changed, the distributions of the magnetic field and current density are the same as of Fig. 2 (b) even after multiple cycles application of the AC magnetic field. The depth of the penetration of the external magnetic field r_m is given by the following equation,

$$r_m = \beta r_0, \quad \beta = B_m / B_{mp}, \quad (1)$$

where B_{mp} is the full penetration magnetic field and equal to $\mu_0 J_c r_0$. Fig. 2 (c) shows the areas where the AC external magnetic field penetrates and the AC shielding current flows. AC losses are dissipated in these penetration areas. When the AC external field is reduced gradually to zero, the magnetic field and shielding currents in the penetration area become zero as shown in Fig. 2 (d).

If that the bulk temperature is constant during the application of the AC external magnetic field the reduction of the trapped magnetic field occurs at the first cycle of the AC external field and does not depend on the frequency nor on the duration time of the AC external field. However, experimental results were different from those theoretical predictions [5]. The AC losses caused by the magnetic flux movements in the penetration areas raise the bulk temperature, which causes the reduction of J_c and the increase of r_m . If r_m exceeds r_0 , that is $\beta > 1$, then the trapped magnetic field disappears. Therefore, it is considered that influence of the AC external magnetic field on the trapped magnetic field is due to the temperature rise of bulk caused by AC losses.

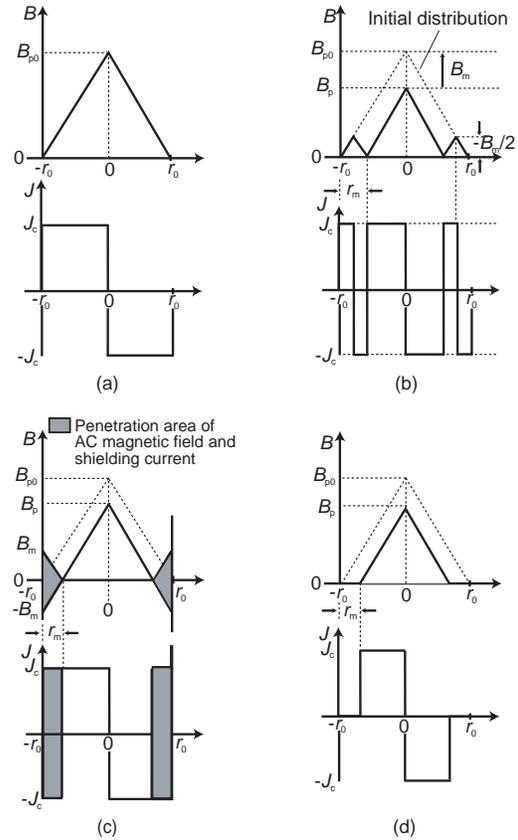


Fig. 2. Distributions of magnetic field and current density in the cylindrical bulk subject to AC external magnetic field of amplitude B_m parallel to the cylinder axis. B_m is lower than the initial peak of the trapped magnetic field B_{p0} .

2.2 Temperature rise of bulk caused by AC losses

In actual applications, bulks of short-cylinder shape are used. Therefore, the temperature rise of a short-cylinder bulk is studied in the following.

It has been shown that the AC loss characteristics of a short cylinder YBCO bulk were well described by a cylinder model of infinite length following the Bean model [6]. Losses in a superconductor cylinder subject to AC external magnetic field of amplitude B_m parallel to the cylinder axis are given by the following equations [4]:

$$Q = \frac{2B_m^2}{\mu_0} \left(\frac{2\beta}{3} - \frac{\beta^2}{3} \right) \quad \text{for } \beta < 1 \quad (2)$$

$$Q = \frac{2B_m^2}{\mu_0} \left(\frac{2}{3\beta} - \frac{1}{3\beta^2} \right) \quad \text{for } \beta > 1 \quad (3)$$

where Q [J/m³/cycle] is the loss per cycle per unit volume. The AC losses caused by the magnetic flux movements in the penetration areas raise the bulk temperature T . T is dependent on the cooling condition of the bulk and can be given by the following equation in the steady state is

assuming the bulk temperature is uniform in the bulk,

$$(T - T_0) = P / \lambda = Q \cdot f \cdot v / \lambda \quad (4)$$

where P [W] is AC loss in the bulk and λ [W/K] is the thermal conduction coefficient from the bulk to the coolant. T_0 is the coolant temperature. f is the frequency of the external field and v the volume of the bulk. J_c is dependent on T and the peak value of the trapped magnetic field B_p becomes temperature dependent. From the Fig. 2 (d), $B_p(T)$ is given by the following equation considering $J_c = dB/dr$.

$$B_p = \begin{cases} \mu_0 J_c(T)(r_0 - r_m) & \text{for } \beta < 1 \\ 0 & \text{for } \beta \geq 1 \end{cases} \quad (5)$$

As T is increased by the AC loss, J_c decreases and r_m increases. Then, B_p decreases and becomes zero when β exceeds 1.

3. Methods to suppress decay of trapped magnetic field and effectiveness of the methods

Obviously from the above study, it is necessary to suppress the temperature rise of the bulk to suppress the decay of the trapped magnetic field. Methods to suppress the temperature rise are;

- To keep the bulk in good cooling condition,
- To reduce the AC losses in the bulk.

3.1 To keep good cooling condition

To suppress the temperature rise, it is necessary that the bulk has good thermal contact to the coolant. A technique to impregnate low melting-temperature metal in the bulk has been developed to improve mechanical integrity of the bulk. This impregnation is also effective to improve the thermal conductivity of the bulk. The improvement of the thermal conductivity is effective to suppress local temperature rise inside the bulk.

Fig. 3 shows an experimental result proving that good cooling is effective to suppress the decay. A bulk impregnated with low melting-temperature metal was set in two different cooling conditions, Case1 and Case2 as shown in Fig. 3 (a). In Case1, all surfaces of the bulk were thermally insulated from liquid nitrogen by a GFRP (Glass Fiber Reinforced Plastic) frame and polystyrene plates. In Case2, the bottom surface was exposed to the liquid nitrogen and has better cooling than Case1. Fig. 3 (b) shows reductions of the trapped magnetic field B_{pc} (peak value) after 10 min application of the AC external magnetic field of 60.6Hz that are plotted against the amplitude of the external magnetic field B_m for Cases1 and 2. Parameters used of the bulk in the experiment are shown in Table 1. Obviously, a reduction of the trapped magnetic field is smaller for the bulk in the better cooling condition (Case2).

3.2 Suppressing AC losses

i) Effectiveness of reduction of AC losses

Fig. 4 shows experimental results proving that reduction of AC losses by increasing J_c of bulks effective to suppress the decay. Time evolutions of the peak of the trapped magnetic fields of two kinds of bulks, Bulk 1 and Bulk 2 with different values of J_c and λ in Fig. 4. The bulks were subjected to AC external magnetic field $B_m = 0.1T$ of 60.6Hz. The parameters of Bulks 1 and 2 are listed in Table 2. Bulk 1 is the same bulk of the same cooling condition of Case1 in Fig. 3. Though Bulk 1 was in worse cooling condition than Bulk2, the decay of the trapped magnetic field of Bulk 1 was slower than that of Bulk 2, because AC losses in Bulk 1 was lower than those in Bulk 2, as is obvious from Fig. 4,

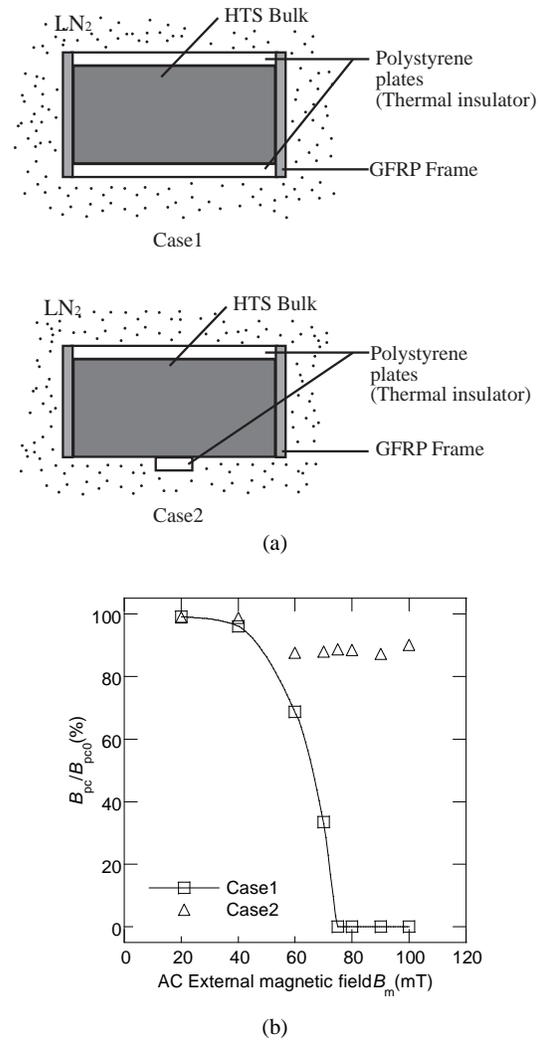


Fig. 3. Experimental result proving that good cooling is effective to suppress the decay of the trapped magnetic field (a) Sample setups. (b) Trapped peak magnetic field B_{pc} after 10 min application of 60.6Hz AC external magnetic field of amplitude B_m in Case1 and Case2. B_{pc} normalized by its initial value $B_{pc0} (=0.71T)$ is plotted against B_m .

Table 1. Parameters of the bulk* used in the experiment.

Bulk size	$\phi 31\text{mm} \times 15\text{mm}$
AC loss**	1.52W
B_{pc0}	0.71T at 77.3K
J_c ***	$4.11 \times 10^7 \text{A/m}^2$
λ ***	0.09 W/K (Case1)
	0.60 W/K (Case2)

*: Impregnated with low melting temperature metal

** : At $B_m=0.1\text{T}$, 60.6Hz

***: Data were estimated from the experimental results

ii) Reducing AC losses using HTS shielding ring

AC losses in a bulk caused by the external AC magnetic field can be reduced by shielding the AC magnetic field. A bulk can be shielded from an AC external magnetic field by placing a low-resistive shorted-ring around the bulk. The time constant of the shorted-ring, or the shielding ring, should be smaller enough than the excitation rate of the external magnetic field for the magnetization of the bulk and larger enough than the cycle of the AC external magnetic field. We conducted an experiment to prove the validity of this method. A shielding ring was a coil made of Bi2223 Ag-sheathed wire and the wire was shorted by soldering. Parameters of the shielding ring are listed in Table 3. The shielding ring was placed around a bulk as shown in Fig. 5. The whole sample shown in Fig. 5 was put in liquid nitrogen bath and in DC magnetic field parallel to the axis of the bulk to magnetization the bulk. After a magnetic field was trapped in the bulk by the field cooling method, the AC external magnetic field was applied parallel to the bulk axis by a copper coil cooled in the liquid nitrogen bath. Fig. 6 shows a time evolution of the trapped magnetic field at the center of the bulk during application of the AC external magnetic field of $B_m=0.1\text{T}$ and 85.2Hz. In the Fig. 6, a time evolution of the trapped magnetic field in the same bulk without the shield ring is also shown to see the effectiveness of the shielding ring. As seen in Fig. 6, effectiveness of the shielding ring is obvious. The trapped magnetic field decayed slowly in the case that the bulk was shielded and was still 89% of the initial value after 300s application of the AC magnetic field. On the other hand, the trapped magnetic field disappeared at 300s in the case that the bulk was not shielded. The initial trapped magnetic fields were the same 0.31T in the both cases of the bulk with and without the shielding ring and the cooling conditions were almost the same (values of λ were $\sim 0.32 \text{ W/K}$).

5. Concluding remarks

Mechanism of the decay of the trapped magnetic field in HTS bulks is reviewed and the theoretical bases for the decay are given. Based on the knowledge of the mechanism of the decay, it is shown that to suppress the decay, it is necessary to suppress the temperature rise of the bulk due to the AC losses. Basically, to suppress the temperature rise, the bulk should be put in good cooling

condition. The reduction of the AC losses in the bulk is also important. However, the AC losses in the bulk are determined by the parameters of the bulk itself if no measures are taken to reduce the AC losses. In the experiment, it is shown that putting a shielding ring around a bulk is effective. The shielding ring can drastically suppress the decay, even if the same bulk is used in the same cooling condition. The experimental result shown in this paper proves the effectiveness of the shielding ring but is preliminary. In the next step, optional design of the shielding rings is to be studied taking account of selection of optional material, necessary volume of the shielding ring, losses in the ring, etc.

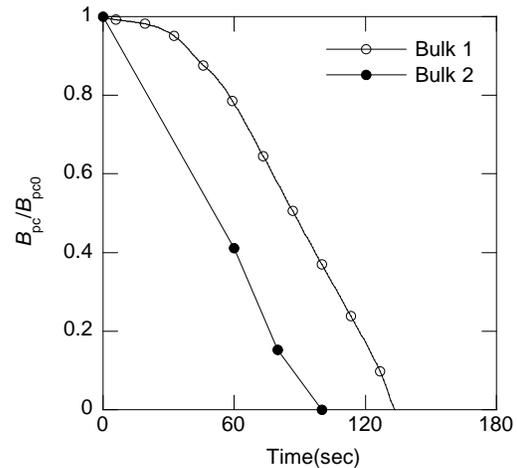


Fig. 4. Time evolutions of trapped magnetic field B_{pc} normalized by B_{pc0} of Bulk 1 and Bulk 2.

Table 2. Parameters of Bulk 1 and Bulk 2.

	Bulk 1	Bulk 2
Bulk size	$\phi 31\text{mm} \times 15\text{mm}$	$\phi 46\text{mm} \times 21\text{mm}$
AC loss at 77.3K	1.52W at 60.6Hz	4.21W at 60.6Hz
B_{pc0}	0.71T at 77.3K	0.16T* at 77.3K
J_c	$4.11 \times 10^7 \text{A/m}^2$	$1.61 \times 10^7 \text{A/m}^2$
λ	0.09W/K	0.68W/K

*: B_{pc0} of Bulk2 is the value measured at 5mm above the bulk surface.

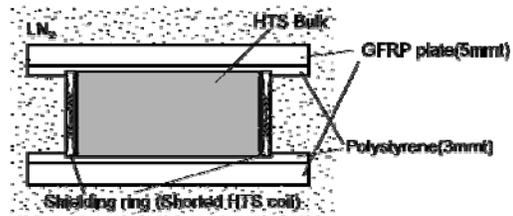


Fig. 5. Arrangement of bulk and shielding ring.

Table 3. Parameters of shielding ring.

HTS wire	Bi2223/Ag sheathed
Size of wire	4.1mm×0.22mm ²
Critical current of wire	80A at 77.3K, 0T
Turn per layer	5
Number of layer	2
Size of ring	ID: φ46.5mm, Height: 20.5mm

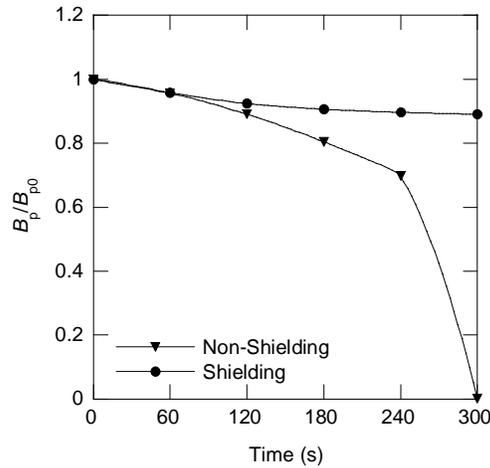


Fig. 6. Time evolutions of trapped magnetic field at center of bulk in cases of with and without of shielding ring. $B_m=0.1T$, 85.2Hz.

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