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Study on suppression of decay of trapped magnetic field in HTS bulk subject to AC magnetic field

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Abstract

The trapped magnetic field in a bulk is decayed and even erased by the application of the AC external magnetic field whose amplitude is much smaller than the trapped magnetic field. In the previous work, an experimental result showed that the decay of the trapped magnetic field was due to temperature rise of the bulk caused by the AC losses. Based on this result, it is considered that the decay can be suppressed by (a) improvement of the cooling of the bulk and (b) reduction of the AC losses. We verified the effectiveness of these methods by conducting an experiment using a recently developed metal impregnated bulk which has high critical current density and improved thermal conductivity.

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Keywords: HTS bulk; AC losses; Trapped magnetic field; Bulk temperature

1. Introduction

Compact and high-performance electric motors and actuators can be realized by using HTS bulks. The HTS bulks in these electric machines are exposed to AC magnetic field perturbations which cause AC losses in the bulks and affect the magnetic fields trapped in the bulks. In our previous works, it was shown experimentally that the trapped magnetic field was decayed and even erased by the application of the AC external magnetic field whose amplitude was much smaller than the trapped magnetic field [1–3]. The decay of the trapped magnetic field is inconvenient for the applications. Therefore, it is necessary to develop the methods to suppress the decay of the trapped magnetic field. To develop the methods, the mechanism of the decay needs to be clarified. In the previous works, we concluded that the decay was due to temperature rise of the bulk caused by the AC losses [2,3]. Based on this result, it is considered that the decay can be suppressed by (a) improvement of the cooling of the bulk and (b) reduction of the AC losses.

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Recently, a bulk impregnated with low melting point metal was developed [4]. The metal impregnation is effective to suppress the magnetic-thermal instability and improve the flux-trapping performance by improvement of the thermal conductivity and mechanical integrity together with enhancement of effective critical current density. Furthermore, the metal impregnation is considered to be effective to suppress the decay of the trapped magnetic field. However, there may be a possibility that the metal component dissipates eddy-current losses which increase the AC losses. In this work we experimentally investigated the influence of the cooling condition and AC losses on the trapped magnetic field to assess the effectiveness of the suppression methods and the metal impregnation.

2. Mechanism of decay of trapped magnetic field and methods to suppress the decay

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. 1 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. 1 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. 1(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. 1(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. 1(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,

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

where B_{mp} is the full penetration magnetic field and equal to $\mu_0 J_c r_0$ Fig. 1(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. 1(d). The peak value of the trapped magnetic field B_p is given by the following equation;

$$B_p = \mu_0 J_c (r_0 - r_m), \quad \text{for } \beta < 1, \tag{2}$$

$$B_p = 0, \quad \text{for } \beta = 1. \tag{3}$$

The AC losses caused by the magnetic flux movements in the penetration areas rise the bulk temperature T, 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, which means that the trapped magnetic field disappears before the bulk becomes normal. T is dependent on the cooling condition of the bulk. We can assume that T in the steady state is given by the following equation assuming the bulk temperature is uniform in the bulk,

$$(T - T_0) = P/\lambda, \tag{4}$$

where P [W] is AC loss in the bulk and λ [W/K] is the heat conduction coefficient from the bulk to the coolant. T_0 is the coolant temperature.

Obviously from the above discussion, (a) improvement of the cooling of the bulk (increase of λ) and (b) reduction of the AC losses (decrease of P) are effective to suppress the decay of the trapped magnetic field.

3. Experimental

3.1. Trapped magnetic field and AC losses

An experiment was conducted to verify the methods mentioned above to suppress the decay of

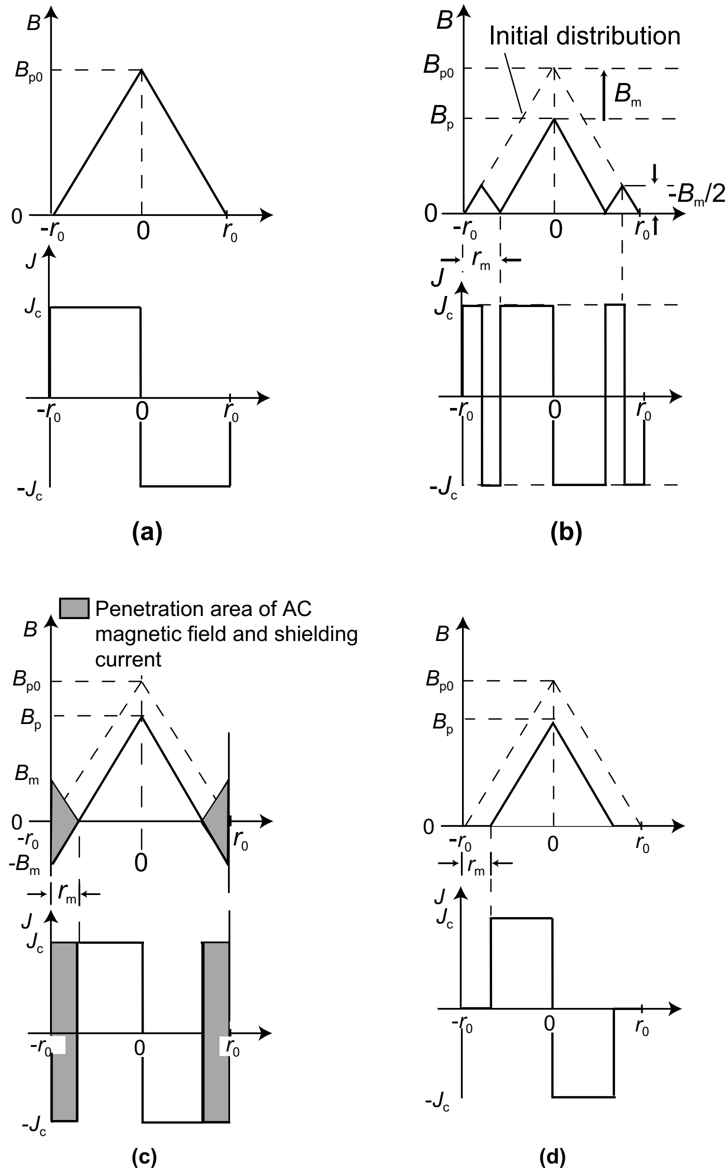

Fig. 1. Distributions of magnetic field and current density in the cylindrical bulk subject to AC external magnetic field of amplitude B_m parallel to the cylinder axis. B_m is lower than the initial peak of the trapped magnetic field B_{p0}.

the trapped field using a YBCO bulk of 31 mm diameter and 15 mm thickness impregnated with low melting point metal. Fig. 2 shows the distribution pattern of the trapped magnetic field of the bulk. The peak of the trapped field is 0.71 T. We measured the AC losses in the bulk with trapped magnetic field in the liquid nitrogen by the method explained in Ref. [1]. The losses per cycle Q_m vs B_m data are shown in Fig. 3 for various frequency f. The losses per cycle are not dependent on f, which means that the AC losses are hysteretic and that the eddy-current losses caused by the metal impregnation do not affect the AC loss characteristics.

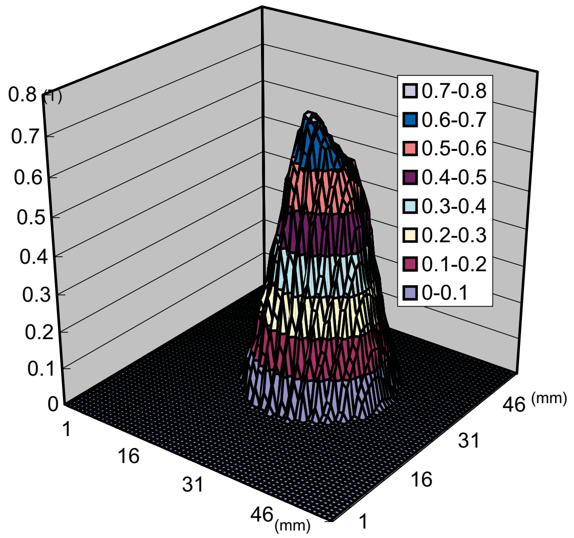

Fig. 2. Distribution pattern of trapped magnetic field of the bulk.

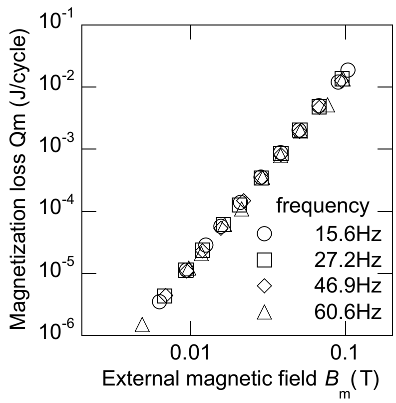

Fig. 3. AC losses per cycle Q_m in bulk with trapped magnetic field vs B_m for various frequency f.

3.2. Temperature rise and decay of trapped magnetic field

The temperature rise and decay of the trapped magnetic field were measured using the metal impregnated bulk in two different cooling conditions, the case 1 and case 2. Sample-setups are shown in Fig. 4(a) and (b) for the cases 1 and 2, respectively. A thermo-couple is for temperature measurement of the bulk and a Hall sensor is for the trapped magnetic field measurement. The sample was placed in a liquid nitrogen bath. Compared with the case 1, the sample of the case 2 is in better cooling condition because a part of the thermal insulation is removed. The values of λ which are estimated from Eq. (4) using the values of P and T in the steady state are 0.0915 and 0.60 W/K for the cases 1 and 2, respectively. Fig. 5 shows time evolutions of the bulk temperature T_{tc} at the point where the thermo-couple is placed, the AC losses P and the trapped magnetic field at the center of the bulk B_{pc} in the case 1. At $t = 0$, the external field $B_m = 0.1$ T/60.6 Hz is applied. P increases as T increases because the AC magnetic field penetrates deeper into the bulk as T increases. There is a peak in the time evolution of P, where B_m is considered to reach to B_{mp} and the B_{pc} disappears. From Fig. 5, T_{tc} is 89.1 K at the point where B_{pc} disappears and less than the critical temperature (about 92 K), which means that the trapped magnetic field disappears not because of the normal transition but because of r_m exceeding r_0. After the peak, P decreases to a steady state value and T_{tc} reaches a plateau. T_{tc} at the plateau is around 93 K which is slightly above the critical temperature of the bulk. When the bulk becomes totally normal, there are no AC losses but in the

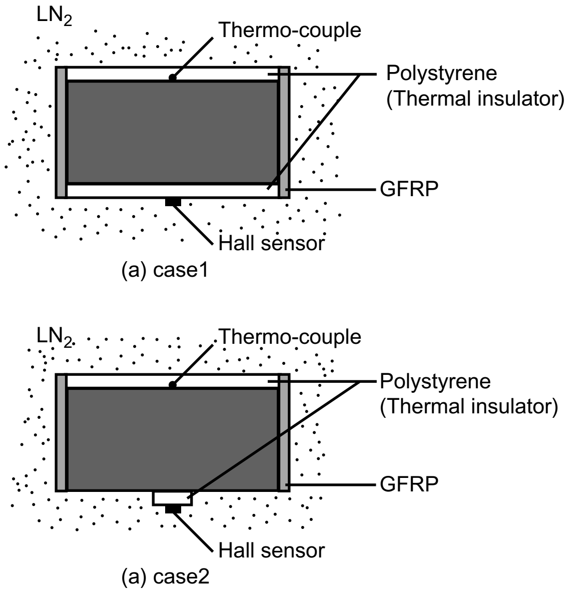

Fig. 4. Sample setups, (a) the case 1and (b) the case 2.

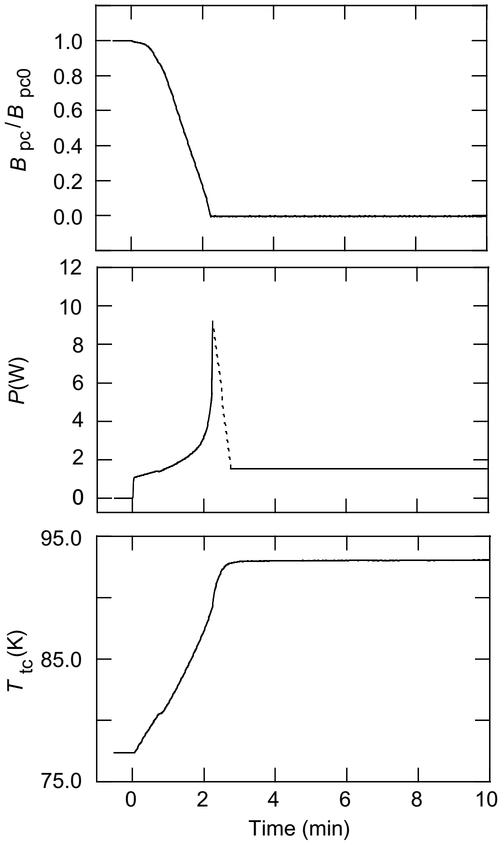

Fig. 5. Time evolutions of bulk temperature T_{tc} AC losses P and trapped magnetic field B_{pc} in the case 1 for $B_m = 0.1$ T/60.6 Hz.

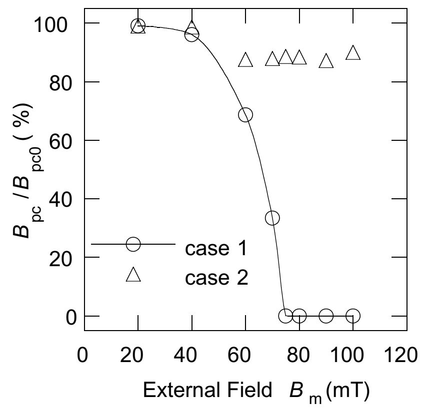

Fig. 6. Trapped magnetic field B_{pc} after 10 min application of 60.6 Hz AC external magnetic field. B_{pc} normalized by its initial value B_{pc0} is plotted against B_m.

plateau area there remains the AC losses to sustain the temperature rise. Therefore, it may be considered that there remains superconducting part locally because of the inhomogeneous temperature distribution. Fig. 6 shows reductions of the trapped magnetic field after 10 min application of the AC external magnetic field of 60.6 Hz that are plotted against B_m for the cases 1 and 2. Obviously, a reduction of the trapped magnetic field is smaller under the better cooling condition (case 2).

4. Concluding remarks

An epoxy-impregnated YBCO bulk of 40 mm diameter and 19 mm thickness was used in the previous experiments [1–3] and its peak trapped magnetic field was 0.31 T. The metal-impregnated bulk used in this experiment has higher J_c because it has higher peak trapped field in spite of the smaller diameter. Therefore, the bulk used in this experiment has smaller AC losses for given amplitude of the AC external field. The AC losses for $B_m = 0.1$ T/60.6 Hz are 1.52 W for the bulk in this experiment and 4.21 W for the bulk in the previously experiments. It took 100 s for the trapped magnetic field to disappear in the case of the previously used bulk subject to $B_m = 0.1$ T, whereas it took longer time (133 s) in the sample of the case 2 as shown in Fig. 5 in spite of the worse cooling condition (values of λ of the bulks in the previous and present experiments are 0.68 and 0.0915 W/K, respectively). Obviously from Fig. 6, better cooling suppresses the decay of the trapped magnetic field more. These results verify the effectiveness of the methods to suppress the decay that are derived from the thermal behavior of the bulk subject to the AC losses. It is also shown that the metal impregnation of the bulk is effective to suppress the decay of the trapped magnetic field causing no extra-AC losses.

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