Numerical Investigation on Applicability of Scanning Permanent Magnet Method to Crack Detection in High-Temperature Superconducting Film

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1 Introduction

As is well known, a critical current density j_{C} is one of the most important parameters for engineering application of high-temperature superconductors (HTSs). Although the standard four-probe method is generally used to measure j_{C}, it may lead to degradation of HTS characteristics. For this reason, some contactless methods such as the inductive method [1], the hall sensor method, and the hall probe method have been proposed. These methods have been applied to the measurement of j_{C}-distributions for a large-area samples such as an HTS tape or wire.

As a novel contactless method, Ohshima *et al.* proposed the standard permanent magnet method for measuring j_{C} in an HTS thin film. While moving a permanent magnet above an HTS film, the electromagnetic force F_z acting on the film is measured. Consequently, they found that the maximum repulsive force F_{M} is roughly proportional to j_{C}. This means that j_{C} can be estimated from the measured value of F_{M}. Although the standard method is used for the determination of j_{C}-distributions or the detection of any cracks in an HTS tape [2], it becomes time-consuming due to the measurement of F_{M} at each measurement point.

Recently, Ohshima *et al.* have proposed a modified permanent magnet method [3]. In the method, the magnet is first placed just above an HTS sample at the constant distance between an HTS surface and the magnet bottom, and it is subsequently moved in the direction parallel to the surface. As a result, they found that a spatial distribution of j_{C} can be obtained from a measured F_z-distribution. In addition, they have concluded that, from the standpoint of the saving of the measurement time, this method is superior to the standard one. In the following, this method is called the scanning permanent magnet method.

In the previous study, a numerical code was developed for analyzing the time evolution of a shielding current density in an HTS film [4]. By using the code, the standard permanent magnet method was reproduced for an HTS film without any cracks. The results of computations showed that, even if the symmetry axis of the magnet approaches the film edge, the maximum repulsive force F_{M} is almost proportional to j_{C}. From this result, we conclude that the standard method is applicable to the measurement of j_{C} even near the edge. However, any cracks were not at all taken into consideration in the code.

The purpose of the present study is to develop a numerical code for analyzing the time evolution of a shielding current density in an HTS film with a crack, and to reproduce the scanning method by using the code. Moreover, we investigate whether or not the scanning method is applicable to the crack detection in an HTS film.

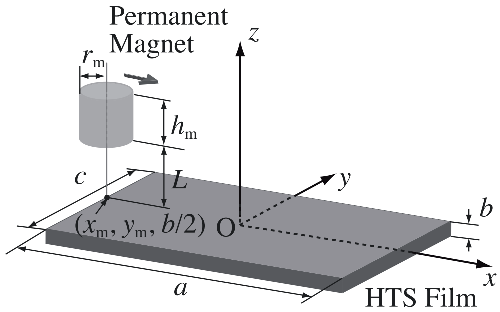

Fig. 1. A schematic view of a scanning method.

2 Governing equation and numerical method

In Fig. 1, we show a schematic view of a scanning permanent magnet method. A cylindrical permanent magnet of radius r_{m} and height h_{m} is placed above a rectangle-shaped HTS film of width a, length c, and thickness b. Also, a constant distance between a magnet bottom and a film surface is denoted by L.

Throughout the present study, we use the Cartesian coordinate system $\langle O : \boldsymbol{e}_x, \boldsymbol{e}_y, \boldsymbol{e}_z \rangle$, where the z-axis is parallel to the thickness direction and the origin O is the centroid of the film. In terms of the coordinate system, the symmetry axis of the permanent magnet can be expressed as $(x, y) = (x_{\mathrm{m}}, y_{\mathrm{m}})$. For the purpose of characterizing the magnet strength, we use the magnitude B_{F} of a magnetic flux density at $(x, y, z) = (0, 0, b/2)$.

As usual, we assume the thin-layer approximation [5]: the thickness of an HTS film is sufficiency thin that a shielding current density can hardly flow in the thickness direction. The shielding current density $\boldsymbol{j}$ is closely related to the electric field $\boldsymbol{E}$ through the J-E constitutive equation: $\boldsymbol{E} = E(|\boldsymbol{j}|)[\boldsymbol{j}/|\boldsymbol{j}|]$. As the function $E(j)$, we use the power law: $E(j) = E_{\mathrm{C}}[j/j_{\mathrm{C}}]^N$, where E_{C} is the critical electric field.

Under the above assumptions, the shielding current density $\boldsymbol{j}$ can be written as $\boldsymbol{j} = (2/b)(\nabla S \times \boldsymbol{e}_z)$ and its time evolution is governed by the following integro-differential equation [5]:

$$\mu_0 \partial_t (\hat{W} S) + \partial_t \langle \boldsymbol{B} \cdot \boldsymbol{e}_z \rangle + (\nabla \times \boldsymbol{E}) \cdot \boldsymbol{e}_z = 0, \qquad (1)$$

where $\langle \ \rangle$ is an average operator over the thickness, and $\boldsymbol{B}$ is an applied magnetic flux density. In addition, $\hat{W} S$ is

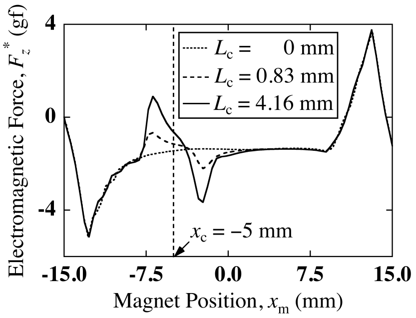

Fig. 2. Spatial distribution of the electromagnetic force F_z^* for $x_c = -5$ mm.

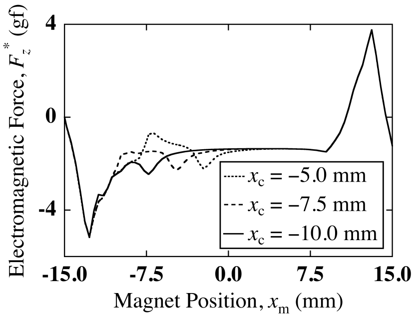

Fig. 3. Spatial distribution of the electromagnetic force F_z^* for $L_c = 0.83$ mm.

defined by $\hat{W}S \equiv \iint_\Omega Q(|\boldsymbol{x}-\boldsymbol{x}'|)S(\boldsymbol{x}',t)d^2\boldsymbol{x}' + (2/b)\,S(\boldsymbol{x},t)$. Here, $\boldsymbol{x}$ and $\boldsymbol{x}'$ are position vectors in the xy-plane. The explicit form of $Q(r)$ is described in [5].

The initial and boundary conditions to (1) are assumed as follows: $S = 0$ at $t = 0$, $S = 0$ on C_0, $\partial S/\partial s = 0$ on C_1 and $\int_{C_1} \boldsymbol{E}\cdot\boldsymbol{t}ds = 0$. Here, C_0 is the outer boundary of the square cross-section of the film, whereas C_1 is the crack surface. In addition, $\boldsymbol{t}$ and s denote a tangential unit vector on C_1 and an arclength along C_1, respectively.

By applying the finite element method and the backward Euler method to the initial-boundary-value problem of (1), the nonlinear boundary-value problem is obtained at each time step. By using the Newton method, it can be solved easily. By means of the above method, a numerical code is developed for analyzing the time evolution of a shielding current density in an HTS film with a crack.

Throughout the present study, the geometrical and physical parameters are fixed as follows: $a = 30$ mm, $c = 10$ mm, $b = 1$ μm, $r_m = 2.5$ mm, $h_m = 3$ mm, $y_m = 0$ mm, $E_C = 0.1$ mV/m, $N = 20$, $B_F = 0.3$ T, and $L = 0.5$ mm. Moreover, we assume that j_C is uniform all over the film: $j_C = 1.5$ MA/cm^2. Incidentally, the magnet is moved from the left end of the film to the right one except for Fig. 4, and the magnet position is controlled as $x_m(t) = -a(2t/\tau_0^* - 1)/2$. Here, τ_0^* is fixed as $\tau_0^* = 140$ s.

3 Numerical results

We investigate whether or not the scanning method is applicable to the crack detection in an HTS film. Throughout the present study, the crack is assumed to be parallel to y-axis and its shape is assumed to be a line segment. The center position of the crack is denoted by $(x, y) = (x_c, 0)$ in xy-plate, and the crack size is given by L_c.

Let us first investigate the influence of the crack size on the F_z^*-distribution. In Fig. 2, we show the spatial distribution of the electromagnetic force F_z^*. We see from this figure that, for the case with $L_c = 0$ mm, F_z^* becomes almost constant for -7.5 mm $\lesssim x_m \lesssim 7.5$ mm. On the other hand, a widely different behavior of F_z^* is observed for the film containing a crack: F_z^* becomes an attractive force F_a for $x_c > x_m$, whereas it becomes a repulsive force F_r for $x_c < x_m$. In addition, the magnitudes of F_a and F_r increase with the crack size L_c. This means that the crack position and size can be estimated from the F_z^*-distribution.

Next, let us investigate the detectable range of a crack. In Fig. 3, we show the F_z^*-distribution for various crack positions x_c's. We see from this figure that, for $x_m \leq -7.5$ mm, F_a cannot be observed because of the edge effect. In conclusion, it is found that, when the crack is located near the film edge, the crack position cannot be estimated from F_a and F_r.

Finally, let us investigate how the F_z^*-distribution is affected by changing the scanning direction of the magnet. For the case where the magnet is moved from the right end to the left one, F_z^* is calculated as a function of x_m and is depicted in Fig. 4. In this figure, two curves of F_z^* intersect at the crack position x_c. From this result, we can conclude that, if two F_z^*-distributions are obtained by using two scanning directions of the magnet, the crack position can be accurately determined from the intersection of two curves for $F_z^*(x_m)$.

References

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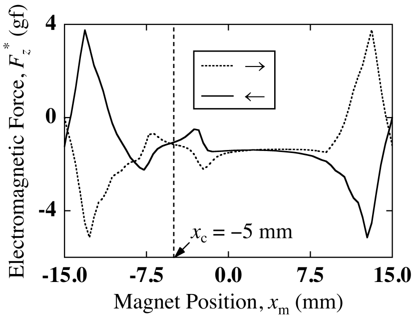

Fig. 4. Spatial distribution of the electromagnetic force F_z^* for $L_c = 0.83$ mm and $x_c = -5$ mm. Here, two types of arrows indicate the scanning direction of the magnet.