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Lorentz Force Density Distribution of a Current Carrying Superconducting Tape in a Perpendicular Magnetic Field

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Abstract-- **The Lorentz force distribution of a high T_c superconducting tape with increasing transport currents in magnetic field (H_a) was visualized. The external magnetic field was applied normally to the coated conductor tape surface after zero-field cooling, and the transport current (I_a) was increased stepwise from 0 to 90 % of the values of the critical current (I_c (H_a)) at applied filed, H_a. The field distribution (H(x)) near the sample surface across the tape width (2w) was measured using the scanning Hall probe method. Applying an inversion to the measured field distribution, we obtained the underlying current distribution (J(x)), from which the magnetic induction, B(x) was calculated with Biot-Savart law. Then Lorentz force per unit length was calculated using F(x)=J(x)×B(x), which appears to be very inhomogeneous along the tape width due to the complicated distributions of J(x) and B(x).**

1. INTRODUCTION

Due to the technology development for long length coated conductors (CC) with high engineering critical current, although the lengths that are needed for large scale application in superconducting electric power devices have not been reached, their application to AC power devices has become more promising [1, 2]. For real applications of CC to the devices, mechanical strength is very important because the devices generally carry current in a magnetic field. The current and magnetic field generate Lorentz force when their directions are orthogonal and the Lorentz force is exerted on the tape. For an example, let transport current flow in the y-direction and let external field be applied in the z-direction. The Lorentz force, of which magnitude and direction can be determined by $\vec{F} = \vec{J} \times \vec{B}$, acts on the tape along the x-direction. And so many researchers have investigated the effect of mechanical stress on the superconducting properties of CC which includes the effect of tensile stress on critical current (I_c) [3, 4]. The Lorentz force, however, is not so simple when the current flows through a CC tape under the external magnetic field due to the high aspect ratio of CC tape.

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AC power devices or superconducting magnets are operated in rather complicated conditions: The transport current flows in the superconductor while the screening current is induced by the external magnetic field. The induced current repels the external field, the direction of which can be severely diverted in the vicinity of the CC, which influences the flux density distribution in the superconductor. Then the circular current occurs in addition to the current which flows between the two current leads. The current distribution cannot be a simple superposition of screening current and transport current. These current and field distributions will generate complicated Lorentz force distribution.

In this study we aim to visualize the Lorentz force density distributions in a current carrying CC in magnetic field applied normally to the surface. Understanding the Lorentz force density distributions in CC can be used to optimize the design of superconducting power devices.

2. EXPERIMENTS

$SmBa_2Cu_3O_{7-\delta}$ (SmBCO) CC tapes with width and length of 4 mm and 30 mm, respectively, were used in this study. A 2.2 μm thick SmBCO film was grown at the Korea Elecrotechnology Research Institute on ion-beam-assisted-deposition (IBAD) template ($LaMnO_3$ (LMO)/ $MgO/Y_2O_3/Al_2O_3$/Hastalloy) using the coevaporation method [5, 6]. The critical current, I_c, and its magnetic field dependence were measured in liquid nitrogen using the standard four probe method and the 1- μV/cm-criterion. The critical current, I_{co}, at 77 K and self-field was 154 A; thus, the critical sheet current density, J_{co}, was 385 A/cm. The external magnetic field, H_a, was applied normally (z-axis) to the tape surface. H_a was varied between 1 and 4000 Oe. The field dependence of the critical current for the SmBCO sample is shown in figure 1.

The field distribution of the sample was measured in the liquid N_2 by the scanning Hall probe method. The Hall probe was an AREPOC product. The active area of the probe was 100 μm × 100 μm and positioned at approximately 350 μm inside the probe body. The surface

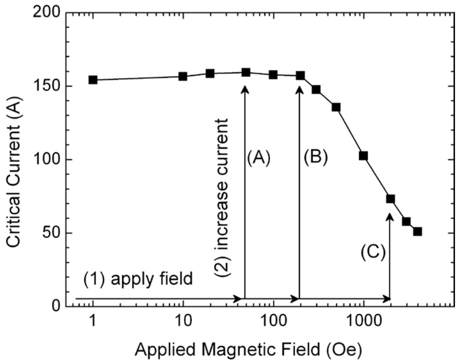

Fig. 1. The critical current as a function of applied field. Experimental conditions (A) H_a = 49.6 Oe, I_a = 20, 40, 60, 80, 100, 120, and 140 A, (B) H_a = 204 Oe, I_a = 23.5, 47.1, 70.6, 94.2, 117.7, and 141.3 A, and (C) H_a = 1982 Oe, I_a = 13, 26, 39, 52, and 65 A.

of the tape was covered by a 50 μm thin Mylar tape. The frontal side of the Hall probe touches the surface of the Mylar tape and slides on it during scanning. Hence, the total distance, δ between the active area of the probe and the tape was about 400 μm. The external magnetic field was applied normally to the CC tape surface after zero-field cooling, and the transport current (I_a) was increased stepwise from 0 to 90 % of the values of the critical current (I_c (H_a)) at H_a = 50, 204, and 1982 Oe. I_a was increased up to 140 A in 20 A-steps for H_a=50 Oe (A), up to 141 A in 23.5 A-steps for H_a = 204 Oe (B), and up to 65 A in 13 A-steps for 1982 Oe (C). For each step, the current distribution was calculated using the iterative inversion process. Before a new set of data was collected for a different value of H_a, the sample was heated up well above the critical temperature in order to remove the trapped magnetic flux. From the measured field distribution data, we obtained the current distribution using the iterative inversion method [7-10].

The inversion method is described briefly below: The normal component of the magnetic field at a distance δ above a superconducting strip is related to the current density distribution by the Biot-Savart's law [11]

$$H_z(x, I_a) = \frac{1}{2\pi}\int_{-w}^{w} \frac{(x-x')J(x', I_a)}{(x-x')^2+\delta^2}dx' + \mu_0 H_a \qquad (1)$$

where $2w$ is the width of the tape, d is the thickness of the SmBCO fillm, and sheet current $J(x) = \int_{-d/2}^{d/2} J(x,z)d$; (in units of A/m like H_a).

Johansen et al. [7] gave the solution of $J(x)$;

$$J_0(n) = \sum_{n'} \frac{n-n'}{\pi}\left\{\frac{1-(-1)^{n-n'}e^{\pi k}}{k^2+(n-n')^2} + \frac{[k^2+(n-n')^2-1]}{[k^2+(n-n'+1)^2]}\frac{[1+(-1)^{n-n'}e^{\pi k}]}{[k^2+(n-n'-1)^2]}\right\} \times H_0(n') \qquad (2)$$

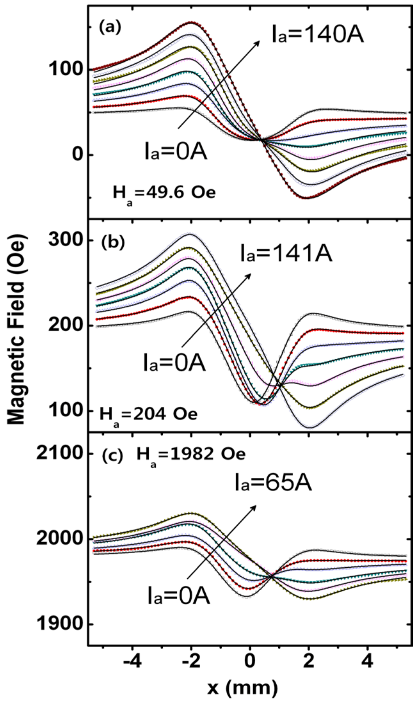

Fig. 2. The field distribution measured near the tape surface by the scanning Hall probe method. The dotted symbols are for the data collected, and the solid lines are for the fitting results in the inversion process.

The iteration process was developed [8] in order to improve the accuracy at sample's edges: $J(x) = \sum_{m=1}^{n} J_m$ calculated on the n-th iteration step is set equal to zero outside the superconducting film, and substituted into equation (1) to obtain the field profile $H_n(x)$. Substituting the difference of $H(x) - H_n(x)$ into equation (2), they calculate the (n+1)-th compensating current $J_n(x)$. They then set $J(x) = J(x) + J_n(x)$ and start the next iteration. After N iterations, the erroneous field, $H(x) - H_N(x)$ becomes infinitesimal, then the correct current profile can be obtained as

$$J(x) = \sum_{n=1}^{N} J_N \qquad (3)$$

Once the current distribution is known, we can find out the flux density distribution, $B_z(x) = \mu_0 H_z(x)$, by substitution of equation (3) into equation (1) at any δ, which is normal component of the flux density distribution. And the parallel component of the distribution can be calculated using the current distribution by equation (4) [11]. Then the surface normal and in-plane Lorentz force at the CC tape can be obtained by the equation, $\vec{F} = \vec{J} \times \vec{B}$.

$$B_x(x,\delta) = \mu_0 \frac{1}{2\pi}\int_{-w}^{w} \frac{-\delta J(x')}{(x-x')^2+\delta^2}dx' \qquad (4)$$

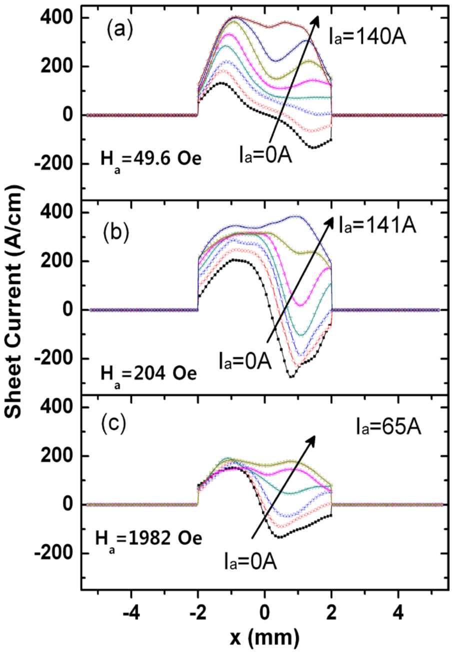

Fig. 3. The sheet current density distribution, $J(x,H_a,I_a)$, calculated by the inversion of the corresponding field data in figure 2.

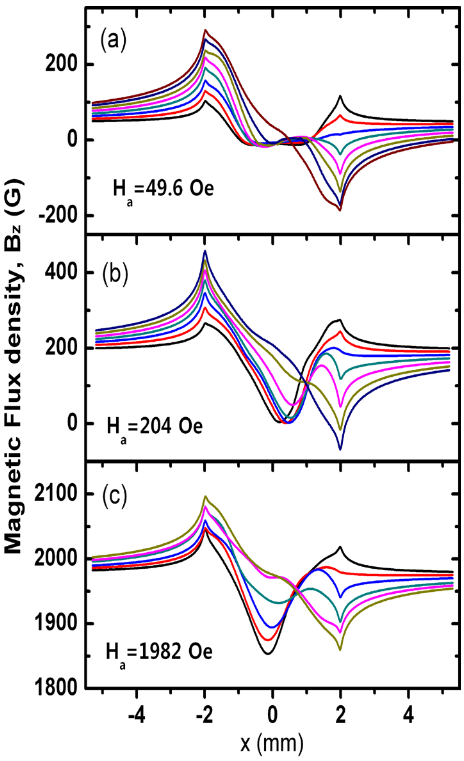

Fig. 4. The normal component of the flux density distributions, $B_z(x,H_a,I_a)$, calculated using the $J(x,H_a,I_a)$ in figure 3 and the equation (1) at $\delta \sim 20$ µm.

3. RESULTS AND DISCUSSIONS

The field distributions measured at H_a = 49.6, 204, and 1982 Oe with increasing transport currents are shown in figure 2(a), (b) and (c), respectively. The experiment conditions were marked with (A), (B), and (C) in figure 1. The peaks at the sample edges of -2, and 2 mm are due to the field repulsion of the superconducting layer, therefore the field intensity was lowered in the center of the tape. However, the observed peaks were not sharp because the measurements were carried out in a position 400 µm away from the sample surface.

The corresponding current distributions obtained by the inversion of the field data measured are shown in figure 3. The peculiar features of the current distributions of this sample, such as the lower J_c values at the edges and the increase of the J_c value with increasing field at $H_a < 300$ Oe, were explained in detail, which can be found elsewhere [9].

The normal component of the magnetic flux density distributions, $B_z(x,H_a,I_a)$, calculated using equation (1) at δ~20 µm, which is the numerical calculation limit in the case, are shown in figure 4. The peaks of the distribution at the sample edges are seen more clearly in figure 4 than those measured in figure 3. In addition, the curvature of the distribution profiles appears in detail, and especially, the Meissner region in the center of the sample for the experimental condition (A) is easily recognized.

As mentioned in the introduction, the field lines were severely diverted due to the field repulsion of the superconducting layer. The x-component of the flux density distributions, $B_x(x,H_a,I_a)$, calculated are shown in figure 5. As one can easily notice, the detailed feature of the $B_x(x,H_a,I_a)$ is almost the same as the $J(x,H_a,I_a)$ in figure 3.

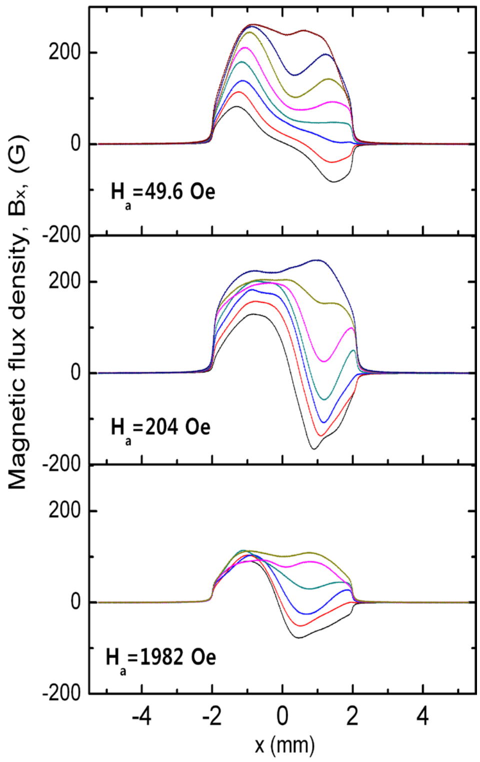

Fig. 5. The x- component of the flux density distributions, $B_x(x,H_a,I_a)$, calculated at the surface of the sample using the $J(x,H_a,I_a)$ in figure 3 and the equation (4).

This can be attributed to the thin film geometry as described in [11]: in thin superconductors in perpendicular field the vortex current is predominantly caused by the curvature of the magnetic field lines and not by the gradient of the flux density. At the surface of the thin superconductor, the field lines are nearly parallel to the surface, and current density is given by the gradient $J_y = \partial H_x / \partial z$ which was from the Maxwell equation of $J_y = -\partial H_z / \partial x + \partial H_x / \partial z$. The J_y can be written as $J_y \cong 2(H_x(z = d/2) - H_x(z = 0))$ since the normal component, H_z is 0 inside the superconductor.

As seen in figure 6, the Lorentz force density distribution is not uniform, instead it is very complicated. The values in figure 6 were underestimated because the calculation distance limit, δ~20 μm, in figure 4 is not the surface of the sample. The surface normal force, F_z, is acting on the top surface of the tape in the field and transport current directions. In this case, the current density distributions seem to dominantly determine the force profiles. Although the H_a was high in the experiment condition (C), the force turned out to be weak. In the case of F_x (force acting in the transverse direction) for the experimental condition (A), the force direction in the left side ($x < 0$) of the tape was opposite to that in the other ($0 < x$). Their directions were toward the tape center as seen in figure 6(d), and so the tape was believed to experience the shear stresses along the tape width. Compared with the F_z, the stronger F_x acted on the tape for the condition (C) while the F_z was stronger than F_x for the conditions of (A) and (B).

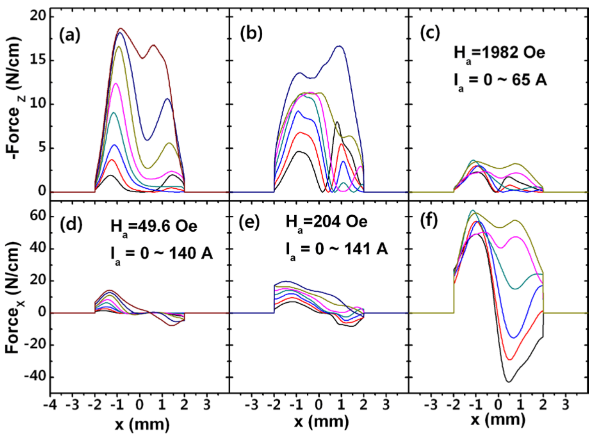

Fig. 6. The Lorentz force density distribution at the sample surface for the $B_z(x,H_a,I_a)$ and $B_x(x,H_a,I_a)$ calculated using the $J_y(x,H_a,I_a)$ and the equations $F_z = -J_y \times B_x$ and $F_x = J_y \times B_z$.

4. SUMMARY

The field distributions for the SmBCO-based coated conductor were measured in liquid N_2 near the surface by the scanning Hall probe method. After the current density distributions were calculated by the iterative inversion of the field data, the normal component and the parallel component of the flux density distributions were obtained by the Biot-Savart equation. Then the Lorentz force density distribution was calculated, which appeared to be very non-uniform over the tape width due to the complicated current and flux density distributions caused by the field repulsion of the superconducting layer. The tape was believed to experience the compressive force, $-F_z$, generated by J_y and B_x and the shear stress, F_x, by J_y and B_z.

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