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Observation of magnetic fields due to persistent currents in a ring made of a coated conductor

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Abstract.

A ring comprising a coated conductor was fabricated. A ring was made first using a biaxially textured Ni tape whose two ends were connected by means of the atomic diffusion bonding technique. Then buffer layers and a YBCO film were deposited on it. All the films were well textured as confirmed by XRD pole figures. The B-H loops, where B and H are the magnetic field at the center of the ring and the applied field respectively, were measured as a function of temperature. The persistent current density (J_c) flowing circularly was estimated from the remanent field of B. In the range of temperature from 72K to 20K, J_c changed from zero to 2×10^5A/cm^2.

Keywords: coated conductor, bonding, YBCO

1. Introduction

Superconducting coated conductors have gained much attentions for the expectations of realizing the potential of high Tc superconductors in large scale devices[1]. The main merit of these coated conductors is the large critical current density under large magnetic fields at the liquid nitrogen temperature[1][2]. A coated conductor comprises a YBCO film and buffer layers, CeO_2/YSZ/CeO_2, on a Ni tape which is biaxially textured by RABiTS process, where the Ni tape is rolled and annealed so as to be recrystallized in cube texture[1][3].

For various applications of the coated conductors, the connection technique of them is important. For example, a ring made of a superconducting tape is a simple interesting structure, where the two ends of the tape are connected so that superconducting current flows circularly along the closed path. We already reported a method for bonding two textured Ni tapes[4]. The process of the atomic diffusion bonding includes several steps; polishing and shaping the ends of two tapes, overlapping and heating them for atomic diffusion bonding while they are mechanically pressed, and final polishing[4]. We deposited a YBCO film on the bonded tapes using buffer layers, CeO_2/YSZ/CeO_2, and achieved $\sim10^5$A/cm^2 of critical current. In this paper, we report the fabrication of a superconducting ring using a coated conductor, where the two ends of a Ni tape were bonded by the atomic diffusion bonding method followed by successive depositions of buffer layers and a YBCO film. We also describe the

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measurements of the circularly flowing persistent currents induced by applied magnetic fields in the ring.

2. Sample preparation

A Ni tape was textured by RABiTS method first and its biaxial texture was confirmed by XRD pole figure measurements. By the atomic diffusion bonding method, we made a ring of the Ni tape(see the inset of Fig.2). The ring diameter and the axial length were 27mm and 10mm respectively. During the bonding process, a special gadget made of alumina bars was used for appling mechanical pressure to the overlap region of the tape without touching the other parts. The bonding area was about 10mm × 0.5mm. Other conditions were same as in Ref.4. In order to polish the surface, a teflon bar, whose diameter is exactly same as that of the ring but reduced slightly by cooling in liquid nitrogen for easy insertion, was inserted into the inside of the ring. At the room temperature, the thermally expanded teflon bar thereby tightly held the ring. Then the ring surface was circularly polished to smoothen the bonded parts. Buffer layers, CeO2(500Å)/YSZ(1000 Å)/CeO2(20Å), were deposited on the ring by e-beam evaporation while the ring was fit around a cylindrical sample holder which was heated up to 650℃ by four halogen lamps and rotated by 30 RPM. The base pressure was ~10^{-6}Torr. The ring surface had been deoxidized by 100mTorr hydrogen gas before it was coated by buffer films. The evaporant materials were metallic Ce and ceramic YSZ. During the deposition of the first CeO_2 layer, the partial pressures of oxygen, water, and hydrogen were ~10^{-8}, ~10^{-6}, and ~10^{-5}Torr respectively. Then a ~ 1000Å thick YBCO film was deposited on the buffer layers by the co-evaporation method. The cylindrical sample holder tightly supporting the ring was rotated by 90RPM in a small reaction chamber filled with 5×10^{-3}Torr oxygen gas. The reaction chamber was connected to a evaporation chamber through an opening. The vapours of co-evaporated Y, Ba and Cu were supplied through the opening and

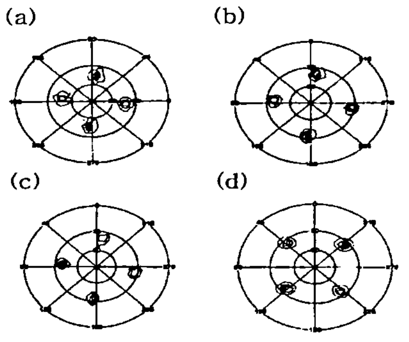

Fig. 1. Pole figures of (a)YBCO[103], (b)YSZ[111], (c)CeO_2[111], and (d)Ni[111]

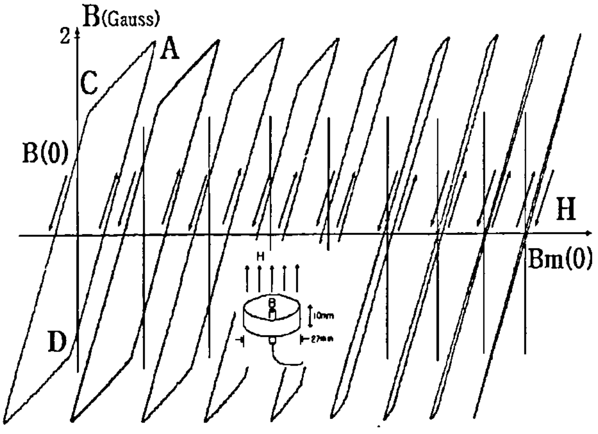

Fig. 2. B-H loops at various temperature. From left, the loops are for 20K, 26K, 33K, 40K, 48K, 55K, 58K, 60K, 76K. The direction of the B-H variation indicated by arrows is reversed in the loop of 76K. The measured loops above 76K are the same as that of 76K. The scale of H-axis is given by dB/dH=1 for the slope "A-D". The slopes "A-C" are very similar for all the temperatures below 60K. Inset; Schematic diagram of the arrangement of the ring and the Hall probe

deposited on the tape. The vacuum in the evaporation chamber was better than 5×10^{-5}Torr, which was due to the effective blocking the oxygen gas leak by the narrow gap between the cylindrical sample holder and the opening frame. The temperature of the tape during deposition was 710±3℃.

Fig.1d shows the pole figure of the biaxially textured Ni tape before the diffusion bonding for the ring shape. However after the tape was bonded to be a ring, it was not easy to check the texture qualities of the films directly because of the difficulty of mounting the ring on the XRD goniometer. Hence the textures were checked after measuring all the electric and magnetic properties of the ring and cutting it into several small pieces in order to mount them easily. In Fig.1c and 1b, CeO_2[111] and YSZ[111] pole figures showed the buffer layers were biaxially textured as the Ni substrate. The YBCO[103] pole figure in Fig.1a shows the crystalline orientations of the YBCO film was coincident with those of buffer layers. That is, the a(b) axis was almost parallel with the rolling axis and the c axis was normal to the surface, which implies they were biaxially well textured at every location on the curved surface.

3. Experimental results and discussion

The inset of Fig.2 shows the arrangement of the ring and the Hall probe to measure the magnetic field B at the center of the ring while the external field H was varied between ~-2 Gauss and 2 Gauss. The field was parallel to the ring axis. The Hall probe was calibrated at the whole range of measuring temperature. Fig.2 shows a typical B-H loop for several temperature. The loops looks like remarkably good parallelograms. The arrows indicate the direction of measured (B, H) point variations. At ~ 62K, the direction of the B-H variation was reversed. Above and below the temperature it was clockwise and counterclockwise respectively. Above T_c the B-H loops were independent of temperature. One of interesting features of the B-H loops is that the slopes between " A " and " C " indicated in Fig.2 are very similar at any temperature. Finally, after turning off the applied field, we observed the remanent field at the center of the ring at a low temperature for an hour and found there was no decay of the field. However at the temperatures higher than ~60K we couldn't easily confirm the absence of decay because the signal size was not enough larger than the noise. Since the remanent fields were almost independent of time at low temperatures, we could estimate the persistent current density from them.

The measured field, B(H), as a function of applied fields, H, is given by the superposition of three components which are the applied field H, $B_m(H)$ due to the ferromagnetic Ni tape, and $B_s(H)$ due to the superconducting current in the film. Hence $B(H) = H + B_m(H) + B_s(H)$. The applied field H is varied from a positive (negative) peak value to a negative (positive) peak value. Since B_m is much smaller than the peak value of H, it is a good approximation that B_s is determined by solely H. Since the field due to superconducting current is perpendicular to the surface at the Ni tape, the subsequent magnetization of Ni tape is small and thereby the effects of the superconducting current on B_m is small. The similar argument was given in Ref. 5 where the energy loss by Ni tape magnetization was neglected in the ac-loss of a coated conductor. Hence it is good approximation that the interaction between B_m and B_s is neglected and they are separately determined by H. Fig.3a indicates the positive and the negative polarities of the remanent fields, $B_m(0)$ and $B_s(0)$, after turning off the positive applied fields respectively. In Fig.2, around 62K, the direction of (B, H) point variation was reversed. Above the temperature, (B, H) point changed clockwise, which was due to $B_m > B_s$. And below the temperature (B,

H) point changed counterclockwise, which was due to $B_s > B_m$. Fig.2 shows B(H) is almost temperature independent above ~75K where B_s vanishes. Hence we can extend the temperature independence of $B_m(H)$ in the full range of temperature of our experiment, which can be justified by small interaction between B_m and B_s. Hence the equation can be rewritten as $B(H,T) = H + B_m(H) + B_s(H,T)$. One can obtain $B_s(H,T)$ by subtracting the temperature independent $B_m(H)$ and the applied field H from the measured field B(H,T). Consequently $B_s(H,T) = B(H,T) - B(H,T_c)$ because $B_s(H,T_c) = 0$. We'll estimate the critical current from $B_s(0,T)$ as a function of T.

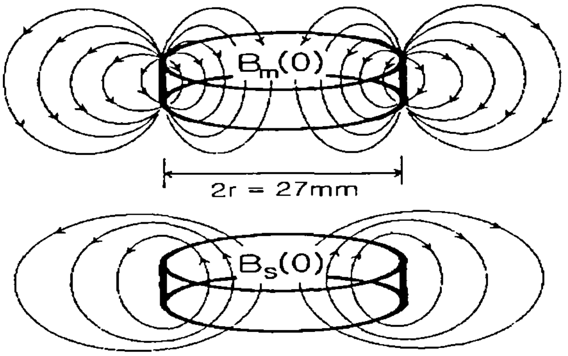

Fig. 3a. Schematic diagram for the explanations of the opposite polarizations of the remanent fields, Bm(0) and Bs(0) after turning off the positive H

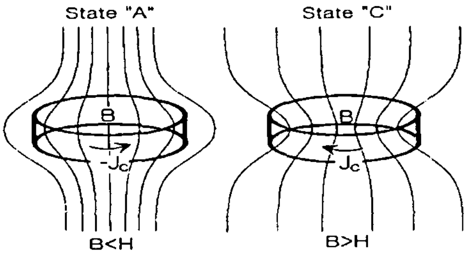

Fig. 3b. Schematic diagram of the field lines for the states, "A" and "C" defined in Fig. 3.

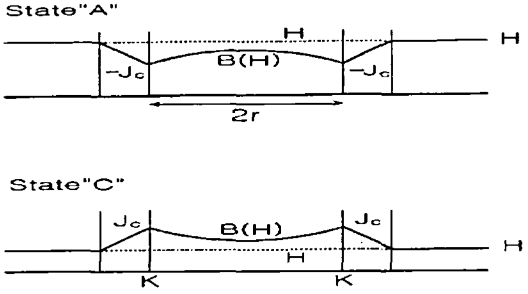

Fig. 3c. Schematic diagram of the distribution of B(H) for the states "A" and "C"

Fig.3a shows the distribution of the magnetic field, $B_m(0)$, due to the remanant magnetization after turing off H. The magnetic field can be easily calculated from the magnetic pole density, $\rho_m = - \nabla \cdot M$, at the upper and lower edges of the ring, where rm M` is the remanent magnetization which is parallel with the ring axis. $B_m(0)$ is anti-parallel to the applied field, which is the reason for the clockwise change of the B-H point in the loop. The field is given by,

$$Bm(0) = -\frac{rtd}{2[(d/2)^2 + r^2]^{3/2}} M$$

Here t and d are the thickness and the width of the film, where d is same as the height of the ring.

When the ring was subject to the applied field at the temperature lower than Tc, the field penetrated into the YBCO film in vortex structure. The current is determined by the Ampere law, $\nabla \times B = \mu_o J$, where B is proportional to the vortex density. When H is small enough so that there is a field free region in the film, one need a complicated calculations to find out the distribution of currents. However once the field penetrates the full thickness of the film and the field free region disappear, the current density reaches the critical value, J_c, at every point according to the critical state model. When H begins to decrease from the peak value, the current densities are reversed to -J_c from the outside of the film. As H keeps decreasing, the current density is reversed to be almost homogeneous -J_c in the full thickness of the film. Since it is a good approximation that the persistent current density remains homogeneous after the field is turned off, it's easy to calculate the field distribution. The field at the center of the loop is given by,

$$B_s(0) = \frac{\mu_0 I}{(d^2 + (2r)^2)^{1/2}}$$

where $I=J_c td$ [6]. Fig.3b and 3c shows the distribution of the magnetic field due to the circular persistent current. The measured field is given by $B(0) = B_m(0)+B_s(0)$, where $B_m(0)$ is constant. B(0) can be estimated from the B-H loops in Fig.2. Fig.4 shows $B_s(0)$ as a function of temperature. Here $B_s(0)$ is given by *subtracting* $B_m(0) < 0$ from $B(0) > 0$. The critical current J_c is also indicated in the figure as given by the above linear relation between $B_s(0)$ and J_c. In the range of temperature from 72K to 20K, J_c changed from zero to 2×10^5A/cm^2.

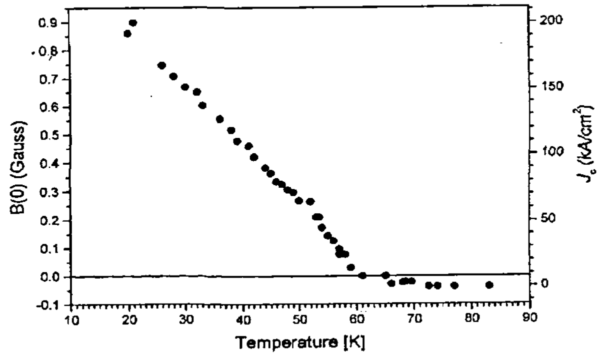

Fig. 4. B(0) and Jc as functions of temperature. The scale for Jc, which are estimated using the equations in the text, is indicated in the left y-axis. Note the zere points of B(0) and Jc are not coincident

The interesting features of the B-H loops, that the slopes between " A "and " C " indicated in Fig.2 are very similar at every temperature, must be understood. The slops, dB/dH are 0.30±0.03 and almost temperature independent. The slope between " A " and " D " is dB/dH = 1, of course. One can find B-H loops with similar shape in the literatures[7]. However the details of the shape are different form those of the ring because the sample shapes in the literatures are not rings. The origin for the slope " A-C " is explained schematically in Fig.3b and 3c. The current density for the state " C " is J_c at any point of the superconducting film. And the current density for the state " A " is -J_c at any point of the film, i.e. completely reversed. In the state between " A " and " C ", the critical current densities are partially reversed inhomogeneously. The current densities are reversed from the outside parts of the film. The point " K " indicated in Fig.3b and 3c is the last point for current reversion. Hence in the state between " A " and " C ", *the total flux captured in the inner circle of* the ring is constant. The diameter of the inner circle is 2r(see Fig.3c)and the captured total flux is given by $\Phi o = \pi r^2 + aI$ where a is the proportional constant for the flux and the total current I which varies from tdJ_c to $-tdJ_c$. The current distribution during the reversion of J_c is complex. However for the simplicity we take the approximation that the portion of the cross-section area where the current is reversed is homogeneous in the film. Hence B_s is proportional to I, i.e. $B_s = k I$ so that the measured field is given by $B(H) = H + kI + B_m$, Combining the two equations, one has

$$B = H\left(1 - \frac{\pi r^2 k}{a}\right) + \frac{k}{a}\Phi o + B_m$$

Since B_m is very small and Φo is constant, the slope is,

$$\frac{dB}{dH} = 1 - \frac{\pi r^2 k}{a}$$

which is temperature independent. In order to calculate the flux, aI, let's approximate the distribution of the field due to " I " as

$$B(x) = (B_r - B_s)(\frac{x}{r})^2 + B_s$$

where x is the distance from center and varies from zero to r and $B_r \equiv B(r)$. One can find the ratio, $B_r/B_s \approx 2.0$ +- 0.1 , from the table of field distribution of a solenoid in Ref.8. where the solenoid shape factor "β" is d/2r = 0.37 for our ring sample. Then the flux is given by

$$\int_0^r B(x) 2\pi x dx = \pi r^2 \frac{B_r + B_s}{2} \approx \frac{3}{2} \pi r^2 B_s = \frac{3}{2} \pi r^2 kI$$

which means

$$a \approx \frac{3}{2} \pi r^2 k$$

Substituting this to the above equation, one has

$$\frac{dB}{dH} \approx \frac{1}{3}$$

which is remarkably similar to the experimental value, 0.30 ± 0.03. One can understand this phenomena qualitatively by Fig.3c. The difference, $B(H)-H=B_s+B_m=kI$ is reversed as $-J_c$ for "A" changes to J_c for "C", where $I = tdJ_c$ and J_c is proportional to the slope of B in the superconductor. As the sign of Bs is reversed, the shape of the distribution of B(H) in the inner circle changes from convex to concave. Since the flux has not yet comes out from the inner region of the circle through the points "K" for "C", the total flux in the inside of the ring is the same as that of "A". Hence B(H) at tht center of the ring must decrease.

The measured critical currents were much smaller than that of coated conductors[1][2], which implies that the superconducting connection in the bonding region of the ring is not good enough. As described in Ref.4 the range of the mechanical pressure for good bonding has a narrow window. Low pressure causes insufficient bonding and high pressure causes deterioration of textures. The ring is an inconvenient structure for appling uniform pressure, that seems to be a main reason for the weakly linked bonding. However our experimental results clearly demonstrated the possibility of the fabrication of a useful closed superconducting circuit like a ring by the atomic diffusion bonding technique.

4. Summary

A ring comprising a coated conductor was fabricated. A ring was made first using a biaxially textured Ni tape whose two ends were connected by means of the atomic diffusion bonding technique, and then a YBCO film with buffer layers were deposited on it. All the films were biaxially well textured as confirmed by XRD pole figures. The B-H loops, where B and H are the magnetic field at the ring center and the applied field respectively, were measured as a function of temperature. After turning off H, we observed the absence of decay of the remanent field at the center of the ring at low temperatures for an hour. The persistent current density J_c flowing circularly was estimated from the remanent field of B. In the range of temperature 72K to 20K, J_c changed from zere to 2×10^5A/cm^2. The detailed structure of the B-H loop could be explained.

Acknowledgements

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References

[1] A. Goyal, D. P. Norton, J. D. Budai, M. Paranthaman, E. D. Specht, D. M. Kroeger, D. K. Christen, Q. He, B. Saffian, F. A. List, D. F. Lee, P. M. Martin, C. E. Klaubunde, E. Harfield and V. K. Sikka, Appl. Phys. Lett. 69, 1795 (1996)

[2] D. P. Norton, A. Goyal, J. D. Budai, D. K. Christen, D. M. Kroeger, E. D. Specht, Q. He, B. Saffian, M. Paranthaman, C. E. Klaubunde, D. F. Lee, B. C. Sales and F. A. List, Science 274, 755 (1996)

[3] Q. He, D. K. Christen, J. D. Budai, E. D. Specht, D. F. Lee, A. Goyal, D. P. Norton, M. Paranthaman, F. A. List, D. M. Kroeger, Physica C 275, 155 (1997)
M. Paranthaman, A. Goyal, F. A. List, E. D. Specht, D. F. Lee, P. M. Martin, Q. He, D. K. Christen, D. P. Norton, J. D. Budai, D. M. Kroeger, Physica C 275, 266 (1997)
C. Y. Yang, S. E. Babcock, A. Goyal, M. Paranthaman, F. A. List, D. P. Norton, D. M. Kroeger, A. Ichinose, Physica C 307, 87 (1998)
Sanghyun Oh, Jaeun Yoo, Kyuhan Lee, JunHo Kim, and Dojun Youm, Physica C 308, 91 (1998)

[4] Doohoon Goo, Sanghyun Oh, JunHo Kim, Kookchae, and Dojun Youm, Physica C 305, 221(1998)

[5] H. R. Kerchner, D. P. Norton, A. Goyal, J. D. Budai, D. K. Christen, D. M. Kroeger, E. D. Specht, Q. He, M. Paranthaman, D. F. Lee, B. C. Sales, F. A. List, and R. Feenstra, Appl. Phys. Lett. 71, 2029 (1997)
H. R. Kerchner, D. P. Norton, A. Goyal, J. D. Budai, D. K. Christen, D. M. Kroeger, M. Paranthaman, D. F. Lee, F. A. List, R. Feenstra, and E. H. Brandt, Phys. Rev. B, 60, 6878 (1999)

[6] John R. Reitz and Frederick J. Milford, Foundations of Electromagnetic Theory (Addison-Wesley Publishing Company, INC, 1960) p. 159

[7] S. Takacs, Handbook of Applied Superconductivity edited by Bernd Seeber (Institute of Physics Publishing, 1998) p. 79
C. P. Poole, Jr. H. A. Farach, R. J. Creswick, Superconductivity (Academic Press, 1995), p. 385

[8] F. Zerobin and B. Seeber, Handbook of Applied Superconductivity edited by Bernd Seeber (Institute of Physics Publishing, 1998) p. 500