Superconductivity and Cryogenics
Vol.11, No.2, (2009), pp.11~14

The comparison of critical currents measured by hall probe and transport methods for HTS coated conductor

Nam-Jin Lee [1], Sang-Soo Oh [2,*], Ho-Sup Kim [2], Dong-Woo Ha [2], Hong-Soo Ha [2], Rock-Kil Ko [2], Tae-Hyung Kim [2], Hae-Jong Kim [2], Kyu-Jeong Song[3], Seung-Hyun Moon [4], Do-Jun Youm[1]

[1]Department of Physics, KAIST, Daejeon 305-701, Korea
[2]Korea Electrotechnology Research Institute, Changwon, Kyungnam 641-120, Korea
[3]Division of Science Education (Physics), Chonbuk national University, JeonJu 561-776, Korea
[4]Superconductor, Nano & Advanced Materials Corporation, Anyang, Gyonggi, Korea

Received 27 April 2009; accepted 11 May 2009

Abstract-- **We estimated the critical current distribution of the long length CCs using hall probe method, and checked the reliability by comparing with the four-probe dc transport method. The deviation ratio of $I_{c\text{-}T}$ (a measured critical current by four probe dc transport method) and $I_{c\text{-}H}$ (calculated critical current by formula (3).) was nearly smaller than 12%. The Hall probe method appeared powerful to evaluate the critical current of CCs in a reel to reel system.**

1. INTRODUCTION

Since high-temperature superconductivity (HTS) were discovered in 1986 [1-5], extensive R&D works for commercial of high temperature oxide superconductor and its application to high-field magnets, low-loss transmission cables, Superconducting Magnetic Energy Storage (SMES) are progressing [6-8]. In recent years, most of R&D works concentrated on coated conductor (CC) which is a promising candidate for high performance HTS wires used at the liquid nitrogen temperature [8-10]. Currently, CCs wire has been commercialized by several companies and extensive R&D works for application of HTS.

For the application of HTS coated conductor to superconducting device, we need critical properties of superconductors of a critical temperature (T_c), critical magnetic field (B_c), and critical current density (J_c). The T_c and B_c are intrinsic properties of superconducting materials, but the critical current density is depend on the grain boundary and the pinning properties. The current distribution is also related to the stability, AC loss, and the current carrying capacity of CCs.

Even though the fabrication process conditions are well established enough to achieve highly textured 123 grains, there still remain a lack of uniformity by the presence of high angle grain boundaries or damage from wire handling which lead to limit a current path.

For commercialization of HTS coated conductor, it is essential to develop an apparatus which can measure the critical current distribution of long length HTS CC quickly with reliability.

The widely used methods are a four-probe dc transport method and a nondestructive hall probe method. The former is an exact and reliable method but has a drawback of having possibility of damage of CC caused by the quench and mechanical stress from current leads. The latter is a quick and nondestructive method. But it is an indirect method using magnetic field distribution across the width of CC generated by shielding current under external magnetic field. Therefore it has the possibility of an error in critical current caused by abnormal shielding current distribution.

In this study, we have estimated the I_c distribution using Hall probe measurement and checked the reliability by comparing with I_c obtained by dc transport measurement.

2. EXPERIMENTAL PROCEDURES

We have fabricated the high-J_c SmBCO CCs using the EDDC (Evaporation using Drum in Dual Chambers) process based on thermal co-evaporation [9-10]. The CCs of commercial products were purchased. Both of HTS coated conductors prepared by KERI and the purchased product were selected for investigation of I_c distribution in 77K and self magnetic field. The structure of both CCs is a Cu / Ag / ReBCO / $LaMnO_3$ / IBAD-MgO / Y_2O_3 / Al_2O_3 / Hastelloy C276 / Cu. HTS tapes has been laminated on both sides with 20μm film of copper by electroplating. The deposited superconductor material of KERI and commercial CC are SmBCO and YBCO film prepared by EDDC and MOCVD method, respectively. The width of CCs is 4 mm.

The magnetic field profiles were obtained to examine the longitudinal homogeneity of CCs using R2R system. The tape sample was spot welded between two Hastelloy C276 tapes to transfer it through the tape scanner. The sample was cooled using liquid nitrogen at atmospheric pressure in self field. The magnetic field measurements of sample were done with the Type MULTI-7U model of Arepoc s.r.o., which have a 100 x 100 μm^2 active area in each elementary sensor and have a sensitivity of 50 mV/T.

---

* Corresponding author: ssoh@keri.re.kr

Measuring probe consists of 7 elementary independent Hall sensors, which locate in a raw with an interval of 600 μm. The Hall Probe measures the field component perpendicular to the tape plane. Since the Hall probe signal was very sensitive depending on a distance between the sensor and ReBCO film, the surface of CCs brushed up against the sensor in order to keep the distance constant.

After the hall scanning, samples were characterized by a four-probe dc transport method at 77 K, self-field. The current and voltage lead was soldered using $In_{66.3}$-$Bi_{33.7}$ solder (melting point = 72°C) to prevent I_c degradation from thermal shock. The critical current was determined using a 1 μV/cm criterion.

3. RESULTS AND DISCUSSION

Fig. 1 shows the principle of scanning hall probe method. The magnet is located above superconductor film. External magnetic field is 400G. In case of $H < H_{c1}$, the shielding current in the superconductor is generated by Meissner effect, external magnetic field is perfectly repelled by shielding current. For $H > H_{c1}$, vortex are penetrated from edge to the center of superconductor, and shielding current is generated with a value of critical current density in the region where vortex exist. When external field is B^*, vortex penetrates in the middle of superconductor. As external field increase above B^*, the slope of magnetic field profile maintains but the magnetic field at the center of superconductor increases as shown in Fig. 1(a). The relationship between J_c and B^* is as following [11]

$$J_c \propto \frac{\partial H}{\partial x} = \frac{2B^*}{d} \tag{1}$$

where d is a width of coated conductor. When constant external magnetic field $2B^*$ is applied on the samples which have different critical current density, the magnetic field profile is different as shown in Fig. 1(b).

We defined ΔB as difference between max. and min. magnetic fields across the width of CCs as shown in fig. 1 (b). In this case, ΔB is proportional to the critical current density. Therefore critical current density can be calculated by measuring the ΔB. The relationship between J_c and ΔB is as following

$$J_c \propto \frac{\partial H}{\partial x} = \frac{2\Delta B}{x} \tag{2}$$

To obtain ΔB, we use multi array hall sensor which is located across the width of superconducting tape as shown in Fig.1(c).

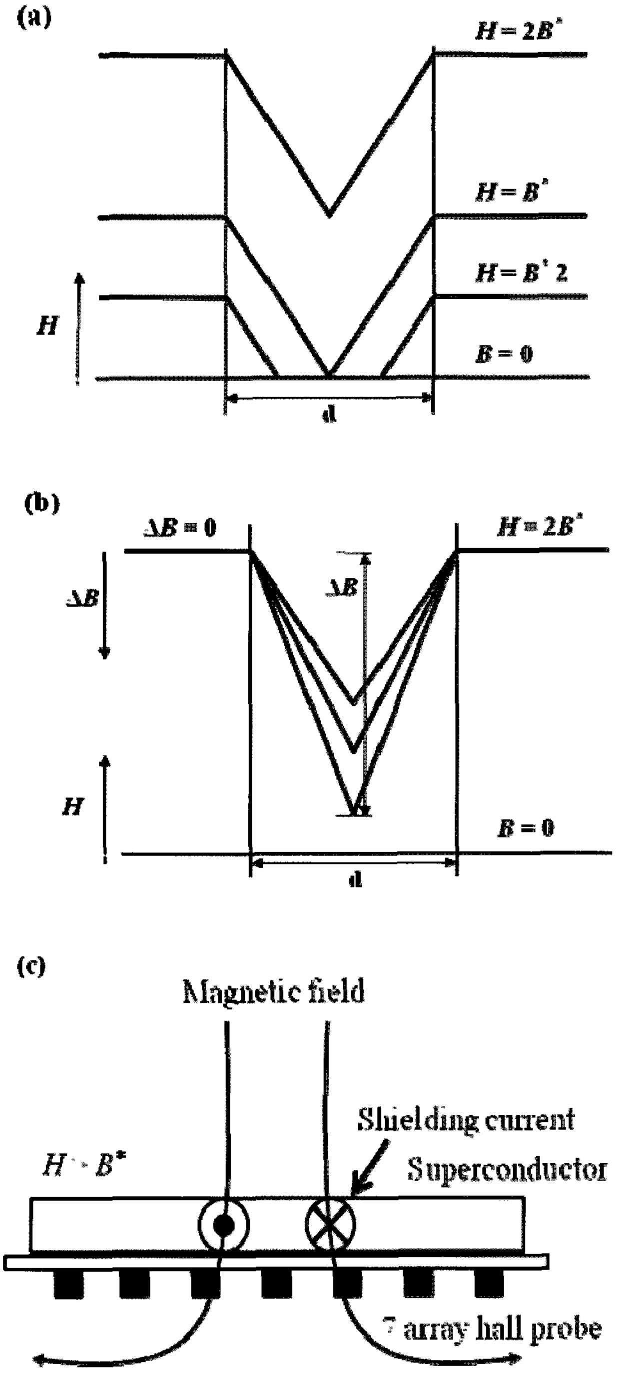

Fig. 1. The schematic diagram showing a principle of hall probe method. (a) The profile of magnetic fields in case of constant J_c, and various external fields. (b) The profiled of magnetic fields in case of constant $2B^*$ and different critical current densities. (c) The layout of scanning hall probe method.

Fig. 2 shows conventional magnetic field profile across the width of CCs (solid circle) and fitting line using Bean model (dash dot line) for determining a calculated I_c. The magnetic field with $H = 400$ G, which is large than B^*, was applied to make magnetic field penetrate into superconductor. First, we calculated the critical current, $I_{c\text{-}H}$, using following formula,

$$I_{C-H} = k\mathrm{x}\Delta B \tag{3}$$

where, the parameter k is determined by the following parameters; (1) the distance between superconductor layer and hall probe sensor, (2) the width of CCs tape. The parameter k can be changed according to the structure and size of CC tape. Alternatively, *k* value can be easily obtained by means of the following equation,

$$k = \frac{I_{C-T}}{\Delta B_{\min}}. \qquad (4)$$

where, $I_{c\text{-}T}$ is a critical current measured by four probe dc transport method in a section of long tape. The ΔB_{min} is a minimum value in the ΔB distribution in the section.

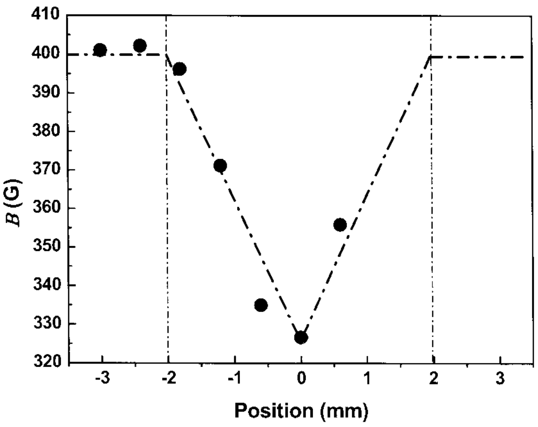

Fig. 2. The magnetic field penetrated into a center from the edge of the superconducting SmBCO film. Dash dot line is fitting line by using Bean model and solid circle is measured value.

We intended to estimate the critical current distribution of the long length CCs using measured I_c by the four-probe dc transport method and the hall measure data in short section. The ΔB distribution of the purchased CC with the length of 1671 cm was measured. After plotting the ΔB profile, a 6.5 cm long reference sample was cut at the end part of 1671 cm to measure $I_{c\text{-}T}$ by four-probe dc transport method as shown in fig. 3 (a). The ΔB_{min} and $I_{c\text{-}T}$ at reference sample are 21.04 G, 88.5 A in the interval of the voltage taps of 3 cm, respectively. From these results, we obtained k of 4.15 using equation (4) and $I_{c\text{-}H}$ was calculated by equation (3). Fig. 3 shows the profiles of ΔB and $I_{c\text{-}H}$ for 1671 cm-long purchased CCs. The average ΔB, standard deviation, min. ΔB and max ΔB are 21.1 G, 0.85, 16.8 G and 23.4 G, respectively. The average $I_{c\text{-}H}$, standard deviation, min. $I_{c\text{-}H}$ and max $I_{c\text{-}H}$ are 87.5 A, 3.55, 69.74 A and 97.30 A, respectively.

$I_{c\text{-}H}$ and $I_{c\text{-}T}$ were compared in the length of 100 cm. After measuring min. ΔB in the full length of 1671 cm, $I_{c\text{-}T}$ was measured at the region of 90 cm. The $I_{c\text{-}T}$ at region of 90 cm was 76.5 A for purchased CCs. Fig. 4. Shows the profiles of $I_{c\text{-}H}$ (line plot) and $I_{c\text{-}T}$ (bar plot) measured with 8 cm intervals. The average $I_{c\text{-}H}$, standard deviation, min. $I_{c\text{-}H}$ and max $I_{c\text{-}H}$ are 74.67 A, 2.91, 71.67 A and 80.45 A, respectively. The average $I_{c\text{-}T}$, standard deviation, min. $I_{c\text{-}T}$ and max $I_{c\text{-}T}$ are 77.67 A, 1.58, 76 A and 81 A, respectively.

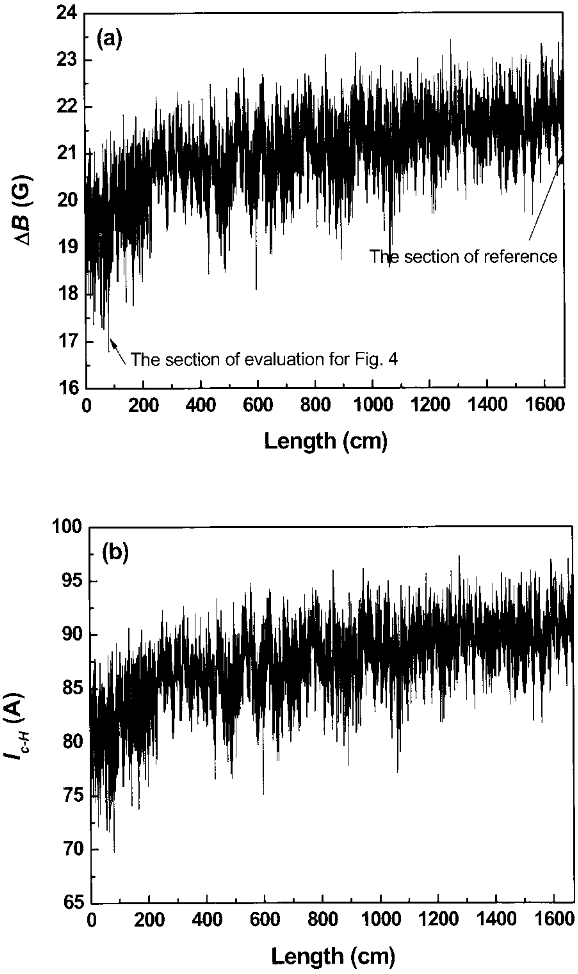

Fig. 3. The profiles of (a) ΔB and (b) $I_{c\text{-}H}$ in the section of 1671 cm. The ΔB_{min}, and $I_{c\text{-}T}$ of a reference section (3 cm) are 21.04 G, 88.5 A, respectively. The coefficient, *k*, is a 4.15 for the purchased CCs.

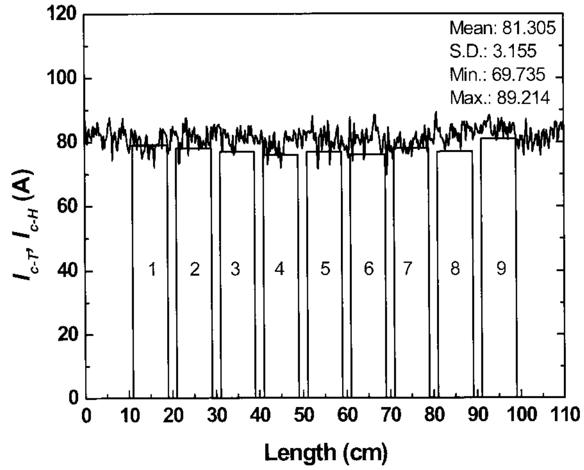

Fig. 4. The profiles of $I_{c\text{-}H}$ (line plot) and $I_{c\text{-}T}$ (bar plot) measured with 8 cm intervals. $I_{c\text{-}T}$ at region of 90 cm is 76.5 A for the purchased CCs.

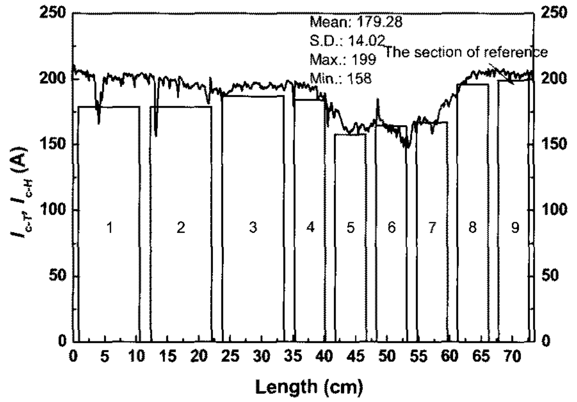

Fig. 5. The profiles of I_{c-H} (line plot) and I_{c-T} (bar plot) measured wth 8 cm or 3 cm intervals. The I_{c-T} at the region of 80 cm is 162 A. The ΔB_{min}. and I_{c-T} of the reference section (3 cm) are 79.691 G, 199 A, respectively. The coefficient, *k*, was a 2.50 in KERI CCs.

TABLE I
THE DEVIATION RATIOS ((I_{c-T}-I_{c-H})/ I_{c-T} X 100)).

Section number	(I_{c-T}-I_{c-H})/ I_{c-T} x 100)	
	Sample I (in fig. 4)	Sample II (in fig. 5)
1	8.72	7.30
2	6.04	12.60
3	1.19	-0.32
4	5.48	0.24
5	6.92	-0.26
6	2.48	9.82
7	3.26	5.03
8	-0.06	1.45
9	0.67	-0.38
Max.	8.72	12.60
Min.	-0.06	-0.38

For comparison of I_{c-H} and I_{c-T}, we prepared CCs with the length of 90 cm with high critical current in KERI. The I_{c-T} at region of 80 cm is 162 A. Fig. 5 Shows the profiles of) I_{c-H} (line plot and I_{c-T} (bar plot) measured with 8 cm or 3 cm intervals. The ΔB_{min}. and I_{c-T} of reference section (3 cm) are 79.691 G, 199 A, respectively. The coefficient, *k*, is a 2.50. The average I_{c-H}, standard deviation, min. I_{c-H} and max I_{c-H} are 172.42 A, 18.69, 148.34 A and 199.75 A. The average I_{c-T}, standard deviation, min. I_{c-T} and max I_{c-T} are 179.28 A, 14.02, 158 A and 199 A, respectively.

From Fig. 4 and 5, it is seen that I_{c-T} distribution tends to coincide with the min. ΔB. However, the critical current distributions obtained by the two different methods do not coincide with each other as shown in table 1. The deviation ratio was nearly smaller than 12%. It is thought that the size and shape of defects affects the shielding current distribution that is deviated from conventional distribution, resulting in different ΔB. The relationship between defects and ΔB is on investigation and it will be reported in elsewhere.

4. SUMMARY

We have estimated the I_c distribution using Hall probe measurement and checked a reliability by comparing with a transport I_c. The Hall probe method appeared powerful to evaluate the critical current of CCs in a R2R system. Using the Bean model ($I_c \propto \Delta B$), we calculated I_c from the hall probe measurement data. The deviation ratio, ((I_{c-T}- I_{c-H})/ I_{c-T} x 100), was nearly smaller than 12%.

ACKNOWLEDGMENT

This research was supported by a grant from Center for Applied Superconductivity technology of the 21st Century Frontier R&D program funded by the Ministry of Education Science and Technology, Republic of Korea.

REFERENCES

[1] J. G. Bednorz and K. A. Müller, "Possible High T_c Superconductivity in the Ba-La-Cu-O System", *Z. Phys.* B 64, pp. 189-192, 1986.
[2] M. K. Wu, J. R. Ashburn, C. J. Torng, P. H. Hur, R. L. Meng, L. Lao, Z. J. Huang, Y. Q. Wang, C. W. Chu, "Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure", *Phys. Rev. Lett.* 58, pp. 908-910, 1987.
[3] H. Maeda, Y. Tanaka, M. Fujinoto, and T. Asano, "A New High-T_c Oxide Superconductor without a Rare Earth Element", *Jpn. J. Appl. Phys.* 27, pp. L209-L210, 1988.
[4] Z. Z. Sheng and A. M. Hermann, "Bulk superconductivity at 120 K in the Tl-Ca/Ba-Cu-O system", Nature 332, pp. 138-139, 1988.
[5] A. Schilling, M. Cantoni, J. D. Guo and H. R. Ott, "Superconductivity above 130 K in the Hg-Ba-Ca-Cu-O system", *Nature* 363, pp. 56-58, 1993.
[6] A. Ishiyama, S. Akita, H. Kasahara, H. Sakaguchi, "Research and development of HTS-SMES system", *Physica C* 357-360, pp. 1311-1314, 2001.
[7] M. Nassi, "HTS prototype for power transmission cables: recent results and future programmes", *Supercond. Sci technol.* 13, pp. 460-463, 2000.
[8] Y. Shiohara, M. Yoshizumi, T. Izumi, Y. Yamada, "Current status and future prospects of Japanese national project on coated conductor development and its applications", *Physica C* 468, pp. 1498-1503, 2008.
[9] H.S. Kim, H.S. Ha, T.H. Kim, J.S. Yang, R.K. Ko, K.J. Song, D.W. Ha, N.J. Lee, S.S. Oh, D.J. Youm, Chan Park, "The deposition of $Sm_1Ba_2Cu_3O_{7-\delta}$ on $SrTiO_3$ using co-evaporation method", *Physic C* 460-462, pp. 1361-1362, 2007.
[10] S S Oh, H S Ha, H S Kim, R K Ko, K J Song, DWHa, T H Kim, N J Lee, D Youm, J S Yang, H K Kim, K K Yu, S H Moon, K P Ko and S I Yoo, "Development of long-length SmBCO coated conductors using a batch-type reactive co-evaporation method", *Supercond. Sci. Technol.* 21, pp. 1-6, 2008.
[11] Charles P. Bean, "Magnetization of High-Field Superconductor", *Reviews of Modern Physics*, pp. 31-39, 1964.