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The Characteristics of Bi-2223/Ag Conductor for High Field Application

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***Abstract*—For the development of high magnetic field application using high temperature superconductor (HTS), Bi-2223/Ag tape is one of the promising materials because of its high current capacity and upper critical field. However, Bi-2223/Ag tape shows very strong anisotropy and significant deterioration of critical current in the magnetic field. To explore the possibility of HTS in high field applications, we evaluated the critical current and index value of Bi-2223/Ag conductor in high magnetic field. The Bi-2223/Ag tape was characterized as a function of increasing and decreasing field. The temperature dependence was also examined lower than 4.2 K. All measurements were carried out with hybrid magnet system up to 30 T and the experimental results are reported.**

***Index Terms*—Bi-2223/Ag conductor, critical current, high magnetic field, index value.**

TABLE I
SPECIFICATIONS OF Bi2223/Ag CONDUCTORS

	DI-BSCCO **High current type**	**DI-BSCCO** **High strength type**
Average width	4.3 ± 0.2 mm	4.2 ± 0.2 mm
Average thickness	0.22 ± 0.02 mm	0.22 ± 0.02 mm
Max. tensile stress @RT	100 MPa	170 MPa
Max. tensile stress @77.3K	135 MPa	210 MPa
Max. bending diameter @RT	70 mm	50 mm
Critical current @77.3K, 0T	> 140 A	> 110 As

I. INTRODUCTION

A new project to develop an nuclear magnetic resonance (NMR) spectrometer to overcome 1 GHz (23.5 T) has launched in Japan since 2006 [1]. Due to the upper critical field in low temperature superconductor (LTS), it is well known that the field limitation of magnet constructed by Nb_3Sn and NbTi is around 24 T. To achieve the magnetic fields above 24 T, it is necessary to use the conductor sustaining strong current capacity in high magnetic field. The HTS materials such as Bi-2212 wire, Bi-2223 tape, and YBCO coated conductor give us opportunities to utilize them in high field magnet.

In current stage, the performance of commercial Bi-2223/Ag conductor has improved and advances of conductor are suitable in high field [2]. In HTS insert using Bi-2223/Ag conductor, the tapes in coil are usually exposed to strong magnetic field. The critical current (I_c) of conductor was significantly affected by the external field [3]–[5]. Therefore, the anisotropy and deterioration of critical current should be investigated for designing magnet in advance. In this paper, we present the experimental results of field dependence in Bi-2223/Ag tape (DI-BSCCO by Sumitomo Electric Industries). A sample holder of high current capacity over 1000 A was prepared for measurement. The two conductors were connected to probe by soldering, which was parallel and perpendicular way to the wide surface of tape. Using this probe, the field dependencies as well as anisotropy of critical current and index n was characterized as a function of external magnetic field up to 30 T. When we remind of operating temperature of conventional NMR spectrometer, the critical current characteristics lower than 4.2 K are required. The temperature of cryostat reduced nearly 2 K to investigate the performance of the specimens will be used for HTS insert. The experimental procedures and results are described in detail.

II. EXPERIMENTAL

A. Bi-2223/Ag Conductor

Silver-sheathed multi-filamentary, Bi-2223/Ag tape was used in this work. It is commercially obtained HTS tape, which is so called DI-BSCCO conductor provided from Sumitomo Electric Industries. Table I illustrates the specifications of specimens used in our measurement. The critical current was measured by standard four-probe method at liquid nitrogen with criterion of $1.0\times10^{-4}\ \mathrm{V/m}$. We have examined both of conductors, but the results in high current density type are presented here in detail.

B. Experimental Procedure

Fig. 1 is the schematics which describes experimental setup for present study. The measurements were performed with hybrid magnet system in National Institute for Materials Science. The hybrid configuration, 14 T of superconducting outsert and 16 T of resistive insert magnet, could generate the magnetic field up to 30 T in room temperature bore. For the cooling of

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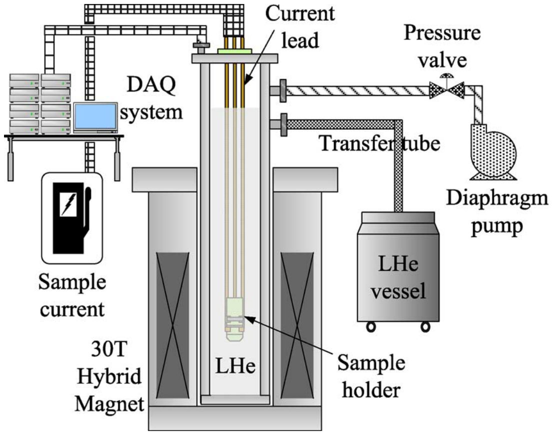

Fig. 1. Schematics of experimental setup for the characterization of Bi-2223/Ag conductor.

Fig. 2. The photo of sample holder for high field measurement.

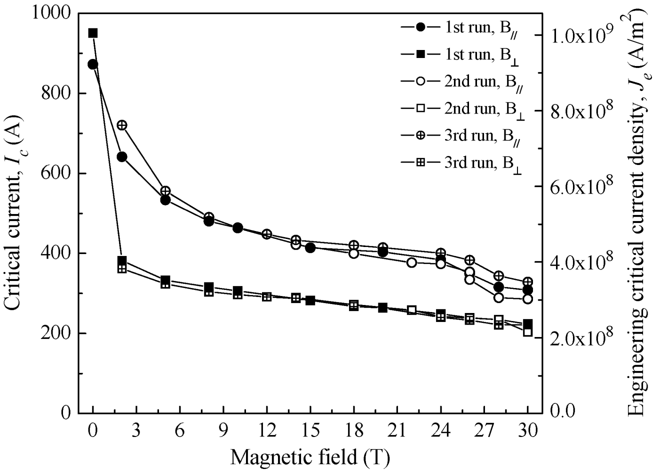

Fig. 3. The reduction and anisotropy of critical current in high magnetic field up to 30 T, 4.2 K.

the sample, cryostat was installed into the bore and liquid helium was transferred in it through transfer tube. In order to cool down below 4.2 K, cryostat was depressurized by the diaphragm pump. The temperature of inside cryostat was controlled by the pressure of cryostat. Most equipment for critical current measurement was basically controlled by computer through GPIB interface for data acquisition as shown in Fig. 1. The transport current for specimens were monitored at the voltage drop across shunt resistance, which was measured by digital volt-meter. We used the ramp rate below 10 A/sec, which did not show any difference in results. The two nano-voltmeters were used for getting a data from each sample.

Fig. 2 describes the photo of sample holder. The sample holder was prepared for the high current capacity over 1000 A. The sample was cut from several hundreds meters in a piece length. The specimens were mounted on the sample holder by soldering, which were placed on parallel and perpendicular direction to external magnetic field. The cold bore of cryostat has a diameter of 52 mm, which limits the size of sample holder. Therefore, total length of specimens in this study was determined at 45 mm length including 5 mm current lead at each side. In our preliminary measurements, it was found that the sample was seriously damaged by lorentz force during measurement. The copper plate was inserted as reinforcement in the bottom of samples to prevent the sample damage from electromagnetic force. The effectiveness of reinforcement was checked. It was also confirmed that copper plate did not affect the critical current results at all.

III. RESULTS AND DISCUSSION

Firstly, we measured the transport properties in Bi-2223/Ag tape as a function of external magnetic field up to 30 T, 4.2 K. The critical current was decided with the criterion of $1.0 \times 10^{-4}\ \mathrm{V/m}$. Fig. 3 shows the test results of HTS specimen. In the figure the symbol shows the averaged value of the two times at same magnetic field in order to minimize the experimental errors. We also repeated the measurements three times from 0 to 30 T as shown in Fig. 3. All data were obtained in increasing magnetic field up to 30 T at 4.2 K. The round symbols are the critical current in parallel magnetic field and rectangles are for perpendicular magnetic field. It is well known that the critical current highly depends on the external magnetic field as shown in figure. The deterioration of critical current was much larger in perpendicular magnetic field than parallel ones [2]–[5]. In each measurement, good consistency was shown in the results at wide range of magnetic field. However the difference was found at parallel fields especially in higher magnetic field region than 24 T. This is not clear in this stage but anomalous phenomenon was observed repeatedly. This behavior will be explained again in latter part.

The temperature of cryostat reduced lower than 4.2 K and then the dependence of critical current was observed. It is thought to be essential to examine the conductor properties at lower temperature than 4.2 K because of operating temperature of conventional NMR spectrometer [9], [10]. The cryostat of liquid helium was depressurized so that we achieve the temperature below 4.2 K. According to the relation shown in Fig. 4, we control the pressure inside of cryostat with diaphragm pump to reduce the temperature nearly 2 K. Before we start to depressurize inside cryostat, the total amount of liquid helium remained in the cryostat was checked and monitored during measurements. The coolant quantity inside of cryostat limited

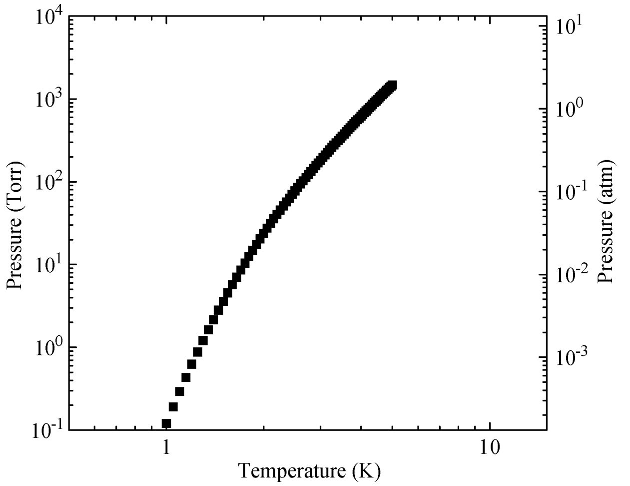

Fig. 4. The relations of pressure vs. temperature of liquid helium [6].

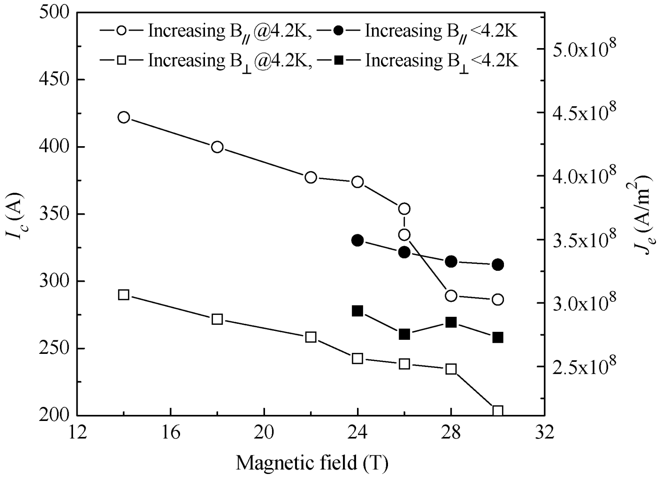

Fig. 5. The temperature and magnetic field dependence of critical current.

TABLE II
THE CORRESPONDENCE OF PRESSURES AND OPERATING TEMPERATURE

B (T)	$B_{//}$		$B_\perp$	
	P (Torr)	**T (K)**	**P (Torr)**	**T (K)**
24	42.263	2.2182	42.666	2.222
26	38.095	2.1752	38.271	2.177
28	34.242	2.1328	34.238	2.132
30	32.412	2.1112	33.792	2.0892

measuring time during depressurization. Fig. 5 shows the temperature dependence of critical current in increasing magnetic field. The results are compared with the ones measured at 4.2 K. The empty and filled symbols are test results of 4.2 K and lower than 4.2 K, respectively. The corresponding temperatures operated in experiment are illustrated in Table II. The critical current around 2.1 K generally shows higher than 4.2 K. Unexpectedly some of round symbols for parallel magnetic field are lower than 4.2 K.

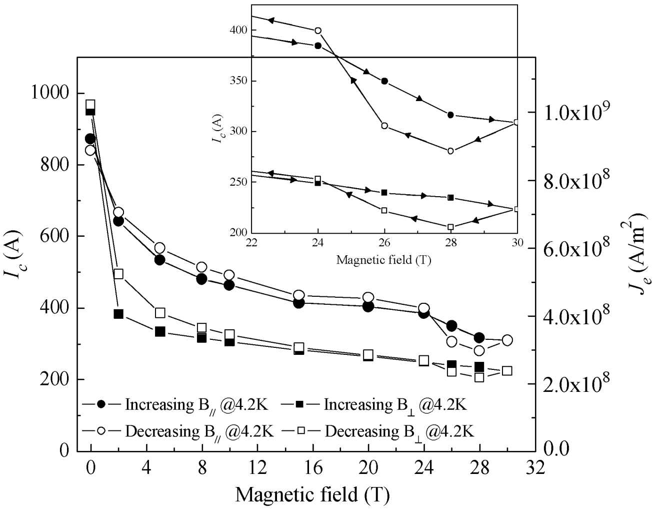

Fig. 6. The hysteric behavior of critical current with respect to increasing and decreasing magnetic field at 4.2 K. The inset enlarges the inversed hysteric behavior at higher field range above 22 T.

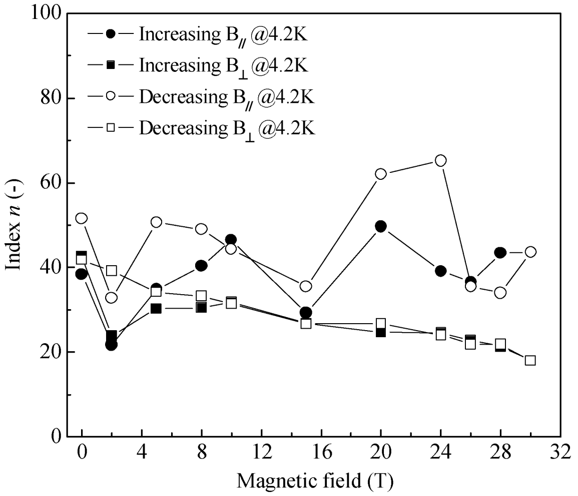

Fig. 7. The index value distribution as a function of increasing and decreasing magnetic field at 4.2 K.

The test results of critical current in increasing and decreasing field can be found in Fig. 6. The round symbols are the critical current in parallel field and rectangles are for perpendicular. The filled and empty symbols mean the critical current in increasing and decreasing magnetic field, respectively. The strong field dependency of HTS specimen was found here as depicted in Fig. 3. Furthermore hysteric behavior is found in the wide region of magnetic field. The reason of enhancement of critical current in decreasing magnetic field was caused by weak links theory, which was well explained by J. E. Evetts and B. A. Glowaki [7]. It is quite noticeable that hysteric behavior is completely inversed in higher field region, especially above 24 T. Similar behavior was already reported in [8], which was considered to be the magnetic field distribution inside specimen.

Fig. 7 describes the dependence of index n on the external field alternation (increasing and decreasing field) as well as its orientation (parallel and perpendicular field). The index n was defined between $0.1 - 1.0 \times 10^{-4}$ V/m of electric field. As one

TABLE III
COMPARISON OF INDEX VALUE

B(T)	**Increasing field**		**Decreasing field**	
	Mean value	**Standard deviation**	**Mean value**	**Standard deviation**
$B_{//}$	38.515	7.9	44.922	18.6
$B_\perp$	27.024	6.64	28.991	7.59

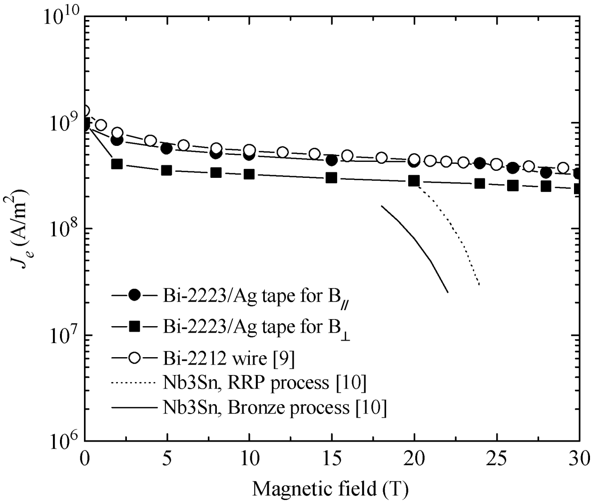

Fig. 8. The comparison of engineering critical current densities with the several kinds of LTS and HTS conductors at 4.2 K.

can be seen in the figure, there is no significant dependency of index on the magnetic field. It is contrast with the results of critical current in the external field. However, slight anisotropy was found as a regard field direction. Table III summarizes the mean value and standard deviations of measured index n. It seems that the data scattered in higher field region. It is because relatively larger noise was introduced in high magnetic field.

Fig. 8 shows the comparison of the engineering critical current densities (J_e) in several HTS conductors with LTS conductors. The magnetic behavior of LTS conductors shows good performance, however, it needs to overcome the strict limitation above 24 T. The HTS conductors such as Bi-2223/Ag, Bi-2212 wire shows enough suitability for higher field applications over 24 T. The J_e has potential of critical current above $3\times10^8\ \mathrm{A/m^2}$ even at 30 T in Bi-2212 wire and Bi-2223/Ag conductor for parallel magnetic field. It is to be seen the J_e of HTS conductor is very promising to aim the high field with a satisfaction. This graph leads us to the conclusion why we need to introduce a HTS conductor for high field applications.

IV. CONCLUSION

The critical current and index value of Bi-2223/Ag superconductor was evaluated in high magnetic field up to 30 T, 4.2 K. The temperature dependence on the critical current at 2.1 K was also observed and compared with the results of 4.2 K. The external field orientations and alternations significantly affected the behavior of critical current of specimens, which showed strong anisotropy and hysteric behavior. However, it was estimated that the index did not highly depend on external magnetic field. The Bi-2223/Ag conductor used in this work reaches at enough potential to realize high field applications over 1 GHz NMR spectrometer.

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