Improved critical current density in DI-BSCCO

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Abstract. High $I_c$ in DI-BSCCO has been demonstrated even in high temperature up to 90K and parallel magnetic field up to 200 mT. This performance is advantageous especially to power cables cooled with pressurized liquid nitrogen, where current and temperature fluctuates in real operation. Recent development has updated the highest $I_c$ at 77K, self-field to 630 A/mm$^2$ in a R&D tape. The evaluation by a scanning magnetic microscope has demonstrated the highest $I_c$ of 900 A/mm$^2$ at the midst of a tape which has $I_c$ of 200 A. This property promises innovative $I_c$ more than 300 A in future DI-BSCCO.

1. Introduction

Bismuth based copper-oxide superconductor, Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$ (Bi2223) bears the highest critical temperature in atmospheric pressure in all of the known substances except mercury and thallium cuprates, which are too poisonous to use for power applications. The crystal of Bi2223 aligns easily along weak coupled planes in Bi-O double layer. This characteristic enables that the powder-in-tube technique, which is a kind of wire manufacturing methods based on deformation processing, produces long wires with high density, c-axis grain alignment and high critical density as a consequence.

Sumitomo Electric has been developing the silver sheathed Bi2223 multi-filamentary tapes since just after the discovery of this substance. When ConTrolled Over-Pressure sintering technique (CT-OP®) had successfully increased the density of the Bi2223 filaments, the tapes had obtained essential properties as an industrial product, which are higher and homogeneous critical current density over the entire length, better mechanical properties and hermeticity for liquid coolant such as pressurized liquid nitrogen used in power transmission cables and also super-fluid helium. The company launched the distribution of the tapes produced with CT-OP to the market under the brand of DI-BSCCO in 2004. DI-BSCCO started from the basic product named as Type H, which has 1 mm$^2$ cross sectional area, 4.3 mm width and 0.23 mm thickness. The family of products was expanded to Type S which has half cross sectional area and narrower width, to Type AC which has the similar slim size to Type S and has twisted filaments for AC use and to Type G which is sheathed by silver-gold alloy for low thermal conductivity required for current leads [1]. As shown in figure 1, long length from 1 km to 2 km had
been already obtained in all the products except Type G, which is 100 meters longest from a small billet. Metallic tapes lamination technique using stainless steel, brass and high conductive copper alloys, was also successfully introduced to improve the mechanical properties without any degradation from original high $I_c$ [1]. The tapes with metallic lamination are called as Type HT, ST and ACT.

While the present $I_c$ in Type H ranges from 140 A to 180 A at 77 K and self-field, higher performance is desired to improve the HTS system’s technical and economic advantage. Sumitomo Electric keeps R&D for seeking higher $I_c$ in DI-BSCCO. This article reports recent accomplishment and a speculation for potential $I_c$.

![Typical longitudinal distributions of $I_c$ in DI-BSCCO Type H, Type S and Type AC](image)

**Figure 1.** Typical longitudinal distributions of $I_c$ in DI-BSCCO Type H, Type S and Type AC

2. **Critical current under the practical conditions of power cables**

As mentioned above, the greatest advantages in DI-BSCCO are long length, high $I_c$ and $T_c$. These features bring the best performance as the conductors for a power cable, which is assumed as one of the most significant application using high temperature superconductors. The magnetic field is generated parallel to the tape plane in the cable core. The magnitude depends on the diameter of the cable core and operation current. For example, in a cable core with 30 mm of outer diameter, maximum parallel magnetic field is 56 mT and 94 mT under 3 kA$_{rms}$ and 5 kA$_{rms}$ operation, respectively. Since HTS power cables are cooled with pressurized liquid nitrogen, the operation temperature is around 77 K. A bit wider temperature rage should be assumed according to design concept. The higher maximum operation temperature reduces the cost for cooling especially in a long-distance cable system. On the other hand, lower operation temperature increases the current capacity due to the improved $I_c$. Consequently, we should assume the highest 100 mT as parallel magnetic field in the temperature range from 65 K to 90 K. Figure 2 shows the temperature dependence of $I_c$ in self-field, 100 mT and 200 mT parallel magnetic field for a Type H tape which has $I_c$ of 200 A at 77 K, self-field. In all the measured temperature range, $I_c$ in 100 mT is almost same as that in self-field. Even at 90 K, $I_c$ stays in about half at 77 K, self-field. This property engages for stable operation in fluctuating current and temperature of real use.
3. Potential critical current and evaluations on partial current density

The larger size of the tape dimension promises the higher $I_c$, however in such a way practical benefits are moderate. A more preferable way is to enhance the engineering current density, $J_e$ that is critical current density per overall cross sectional area including silver sheath. Higher $J_e$ requires higher $J_c$ that is critical current density per filaments area, and higher fill factor that is volume fraction of the filaments in a whole tape. Since the fill factor in the present Type H is around 37%, at the lowest 10% of increase may be possible by using thinner silver tubes and improving deformation process to avoid the geometrical imbalance in the deformed wire. On the other hand, $J_c$ bears far larger room for improvement, which means the $J_c$ in commercially distributed DI-BSCCO is from 400 A/mm$^2$ to 500 A/mm$^2$ at 77K, self-field [1], but potential property is far much higher.

Bi2223 film produced with metal-organic CVD had more than six times higher $J_c$ in spite of its low $T_c$, namely 97 K [2], which was about 14 K lower than that of DI-BSCCO. Hakuraku et al. reported further higher $J_c$ more than 30,000 A/mm$^2$ at 77 K, self-field in their 330 nm thick Bi2223 film produced with sputter deposition and rapid annealing [3]. The difference in $J_c$ between silver sheathed tapes and thin films is attributed to c-axis grain alignment. The distribution of misalignment angles of Bi2223 plate crystals in the tape was evaluated with X-ray rocking curve [4]. When the average misalignment angle is defined as the half width at half maximum of the rocking curve, the $J_c$ in DI-BSCCO is strongly dependent on the mean misalignment angle. While the lowest value is about 6 degrees even for the DI-BSCCO with the highest $J_c$, thin film should not have more than 1 degree. Even only 2 degrees improvement, the impact is great. At 4 degrees, expected $J_c$ is 1,000 A/mm$^2$ [1].

An evaluation of local critical current density is expected as an attempt to find a clue for making a breakthrough. Kiss et al. have evaluated two-dimensional current distribution in a R&D tape which has $I_c$ at 77K, self-field of 200 A. The magnetic self field around the current flowing tape was measured with a scanning probe which consists of 50 µm square hall elements. Using the measured field distribution, sheet current distribution in the tape plane was re-constructed according to Biot-Savart law [5]. Since the specimen was cooled indirectly via copper block which was partially soaked in liquid nitrogen, the temperature of the specimen was 87 K. Figure 3 (a) shows the distribution in the tape that shows 100 A of overall current. From the monitored electric potential, they confirmed that the flowing current was $I_c$ at this temperature. While the longitudinal distribution is uniform, a characteristic profile has emerged in the transversal distribution, where the peak $I_c$ reaches 450 A/cm at midst, $I_c$ drops in both edge portions. The highest characteristic at midst continues longitudinally in all the scanning area of 20 mm long. The peak also seems to continue in entire long length of the
original tape, because $I_c$ in long DI-BSCCO are similar to those in short specimens. Figure 3 (b) shows the current density distribution that was derived from the distribution of sheet current density and filamentary area. Since $I_c$ at the measurement temperature is just half at 77 K, the corresponding peak value at 77K are 900 A/cm and 900 A/mm$^2$ in sheet current density and $J_c$, respectively.

To verify above magnetic analysis, another experiment was carried out. A central portion of 2 mm width was cut out from a specimen with similar $I_c$ of 197 A at 77 K. Two pieces of 2 mm width were united just like a 4 mm specimen in edge to edge contact. Measured $I_c$ of the coupled tape was 230 A, which was 83% of 277 A that is predicted by the above magnetic evaluation. The discrepancy of 17% is accountable as the degradation by cutting. That is because $I_c$ was 161 A in the reunited three pieces of midst and both edge potions, which was 82% of $I_c$ in the original tape before the segmentation. Note that both of the reunited original tape and the united central parts have the same 4 cut surfaces which include local portions damaged by cutting. This accordance has proved validity of the analysis by the scanning magnetic microscope.

![Figure 3](image_url)

**Figure 3.** Current density profiles along width direction at 87 K with the transporting current of $I_c$. (a) sheet current density, (b) current density.

In order to improve $J_c$ in both edge portions as high as that in central portion, improvement of rolling process and filament alignment is desired. As the result of recent development, the highest $J_c$ has been updated to 630 A/mm$^2$ in a 100 mm long R&D specimen which has improved filament alignment and similar size as Type H. The $I_c$ in the tape still stays at 203 A because of its low fill factor. When the fill factor is increased to the average of Type H, the $I_c$ will attain to about 240 A. To achieve $J_c$ higher than 900 A/mm$^2$ as average in overall tape, further improvement is ongoing for optimum filament alignment and rolling condition. If the maximum $J_c$ is obtained as average value in Type H, $I_c$ attains to 340 A.

4. **Conclusion**

High $I_c$ in DI-BSCCO has been demonstrated even in high temperature up to 90K and parallel magnetic field up to 200 mT. This performance expands the possible concept of power cables and enables robust design under the real operation, where current and temperature fluctuate.

Recent development has advanced the highest $J_c$ at 77K, self-field to 630 A/mm$^2$ in a R&D tape. Although $I_c$ in the tape still stays at 203 A because of its low fill factor, $I_c$ about 240 A is possible by optimizing fill factor similar to that of the current Type H. The evaluation by a scanning magnetic microscope has demonstrated the further higher partial $J_c$, which is 900 A/mm$^2$ at the center of a tape with $I_c$ of 200 A. The validity of the magnetic evaluation has been confirmed by the transport $I_c$ measurement of the central 2 mm width portion taken out from the original tape. When the highest $J_c$,
at midst is realized as the mean value of the entire tape, DI-BSCCO will achieve almost twice of the $I_c$ as of today. This result promises innovative $I_c$ more than 300 A in future DI-BSCCO. But this target is not final. Ultimate $J_c$ of Bi2223 is still 10 times higher.

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