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AC loss comparison of Bi-2223 and coated conductor HTS tapes under bending

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Abstract-- **Superconductor is developed for applications in high-power devices such as power-transmission cables, transformers, motor and generators. In such applications, HTS tapes are subjected to various kinds of stress or strain. AC loss is also important consideration for many large-scale superconducting devices. In the fabrication of the devices, the critical current (I_c) of the high temperature superconductor degrades due to many reasons including the tension applied by bending and thermal contraction. These bending or tension reduces the I_c of superconducting wire and the I_c degradation affects the AC loss of the wire. The I_c degradation and AC loss (self field loss) of Bi-2223 HTS and Coated conductor were measured under tension and bending conditions at 77 K and self-field.**

1. INTRODUCTION

Through the advances in cryo-cooler engineering and tape fabrication technology, BSSCO High Temperature Superconducting (HTS) tapes are now commercially available for use in electrical devices and their applications such as magnets, coils and cables. During the last years, YBCO coated conductors have gained a great deal of attention thanks to their high critical current density, above 1 MA/cm^2 at 77 K in self field, weakly dependent on magnetic field [1-3]. In such applications, HTS tapes are subjected to various kinds of stress or strain [4].

In the fabrication of the device, I_c of the HTS tapes degrades due to many reasons including the tension applied by winding and thermal contraction by cooling. Therefore, we need to reduce the operating current and it results in inferior design of the device.

The AC loss in a HTS tapes is usually much lower than the resistive loss in a normal conductor under the same circumstances. Nevertheless, minimization of the AC loss is technically important because the energy is dissipated as heat in the low temperature [5-6].

If we set the operating current with sufficient margin, the device will operate without serious problems. However, the I_c degradation also affects the AC loss, and the AC loss may differ from the designed value which is obtained from sample HTS tape without mechanical load. To estimate the AC loss of the device, it is necessary to investigate the relationship between the I_c and the AC loss.

In this study, the AC loss under self-field was investigated at 77 K on the Bi-2223 and coated conductor. The transport method is used to measure of AC loss and numerical calculation is carried out based on Norris theory to compare with experimental results. The relationship between critical current and AC loss of HTS tapes with partial deformation by mechanical stress was studied.

2. EXPERIMENTAL SETUP

2.1. Bi-2223 and coated conductor tapes

Table 1and Table 2showed the specifications of HTS tape used in this study.

TABLE I
SPECIFICATIONS OF BSCCO TAPE.

Manufacturer	**AMSC**
Width	4.1 ± 0.02 mm
Thickness	0.3 ± 0.02 mm
Material	Bi-2223/Ag/Mg STS
Manufacturing process	Powder in tube
Number of filaments	56
Critical current	115 A

TABLE II
SPECIFICATIONS OF COATED CONDUCTOR TAPE.

Manufacturer	**AMSC**
Width	4.35 ± 0.05 mm
Thickness	0.2 ± 0.02 mm
Max. rated tensile stress (RT)	150 Mpa
Max. rated tensile strain (RT)	0.3 %
Max. rated compressive strain (77 K)	0.3 %
Min. bend diameter	30 mm
Critical current	70 A

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2.2. AC loss measurement system

In this paper, we have investigated the transport AC losses of HTS tapes. It is very difficult to measure AC loss by voltage signal that should be separated from noise because AC loss does not have shape of correct sine waveform due to the nonlinear characteristics. Usually, current signal is large but voltage is very feeble in the superconducting tapes because superconductor operates at low voltage and high current. Voltage signal has influenced on self-field and noise. In some case, FFT (Fast Fourier Transform) method is needed to reduce this noise, but most popular method is to use Lock-in amplifier. The AC loss has been measured using the cancel coil. The reference phase of the applied current was derived by a non-inductive resistor which was in series with the HTS tape sample and Fig. 1 shows arrangement of voltage tab for measured AC loss.

To investigate the relationship between I_c and AC loss, an measurement system is developed, which can measure the I_c and AC loss of HTS tapes under tension and bending.

In this study, AC loss was measured by a cancel coil for reduction of the inductive component. Fig. 2 shows AC loss measurement system that includes the cancel coil.

When the AC current transports in HTS tape, the magnetic flux would be induced in voltage lead of Ampere's law, and voltage would be induced in voltage lead by Faraday's law. The induced voltage can be represented as following equation.

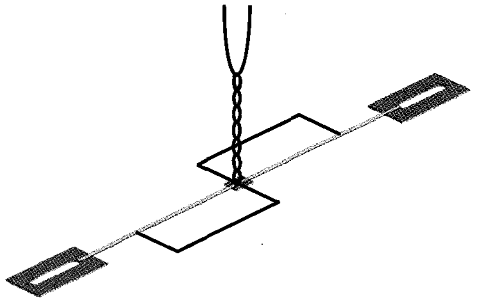

Fig. 1. Arrangement of voltage tab for measured AC loss.

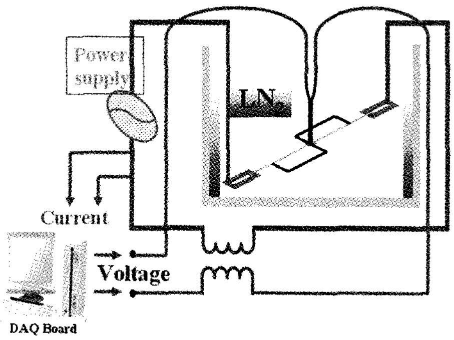

Fig. 2. Scheme of AC loss measurement system.

$$Q = \frac{d}{dt}\int_S (\mu_0 H + \mu_0 M) dS \tag{1}$$

The first term of the integrand in the right hand of this equation is inductive component and the second one is resistive component. However, the first term, inductive voltage, is not AC Loss component. Therefore, it must be cancelled by cancel coil, shown in Fig 3, in order to obtain exact AC Loss. In other words, AC Loss could be calculated by measuring $\mu_0 M$, resistive signal. The AC Loss is determined by

$$Q = \int_0^T i(t)\, v(t)\ dt/l \tag{2}$$

Where i(t) is the transport current with amplitude I, in the sample tape, and v(t) is the voltage signal in lead. T is the period of AC current, and l is the length of superconducting sample tape. The experimental AC loss was compared with the theoretical AC loss by elliptical and strip Norris equation [7] given by

$$Q = \frac{\mu_0 f}{2\pi} I_c \{(2 - F_i)F_i + 2(1 - F_i)\ln(1 - F_i)\} \tag{3}$$

$$Q = \frac{\mu_0 f}{2\pi} I_c \{(1 - F_i)\ln(1 - F_i) + (1 + F_i)\ln(1 + F_i) - F^2\} \tag{4}$$

$$F_i = \frac{I_p}{I_c} \tag{5}$$

I_p is peak value of AC current.
I_c is critical current.
f is frequency of transport current.

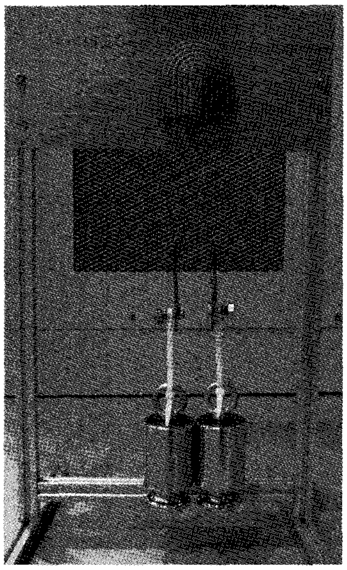

Fig. 3. Mechanical bending device of HTS tape.

Fig. 3 shows that HTS tapes are under the tension of 3 kg and the bending of mechanical load at room temperature. During the experiments, the mechanical load of 3 kg tension is kept and the bending diameter is changed for 100, 90, 80, 70 mm at the Bi-2223 tapes, we have measured I_c and AC loss for each every step. And bending diameter of coated conductor is changed for 60, 50, 40, 30, 20, 10, 5 mm because minimum bending diameter of coated conductors are 30 mm.

3. RESULTS AND DISCUSSION

3.1. AC loss of Bi-2223 tape by I_c degradation

The formation of the Bi-2223 tape is composed of 56 multi-filament. I_c decreases because bending and tension is effected by filament. When bending diameter is 70 mm, I_c decreases about 58 % as shown in the Fig. 4. Mechanical load which applied HTS tapes grows it imposed damage to multi-filamentary in the Bi-2223. However, AC loss was not increased greater than I_c decrements.

Fig. 5 shows AC loss characteristics under mechanical loads. When mechanical load is applied to HTS tape, I_c is decreased, but there is little relation at AC loss.

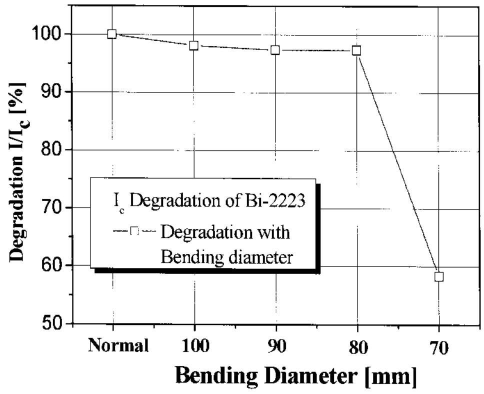

Fig. 4. I_c degradation of Bi-2223 tape with bending diameter.

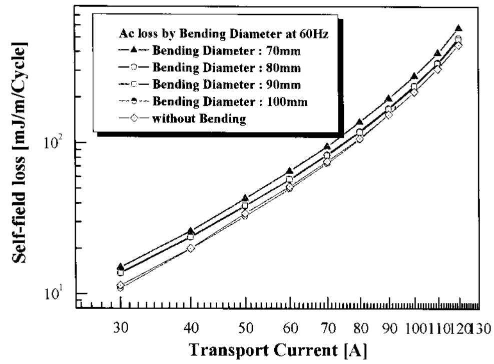

Fig. 5. Self-field loss of SUS-Laminated tape with various bending diameter.

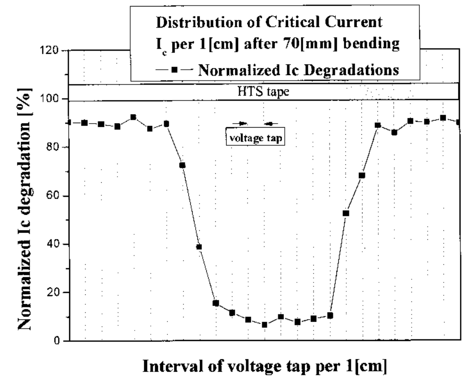

Fig. 6. After 70 mm bending, distribution of I_c interval 1 cm at the HTS tape.

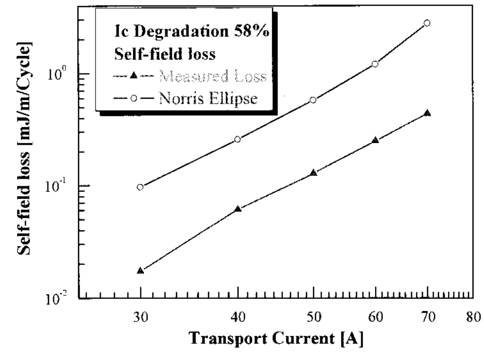

Fig. 7. Self-field loss vs normalized transport current at I_c degradation of 58%.

When bending diameter is more than 80 mm, critical current and AC loss hardly change, and these results are similar to Norris theory. However bending diameter is 70 mm, the results of AC loss are not similar to Norris theory.

This is because I_c is not uniformly distributed along the HTS tape. Fig. 6 shows that the 25 cm length of the tap can be thought as a series connection of twenty-five 1 cm pieces. In the case of 70 mm, I_c degradation of one area is about 10% and the other area is about 90%. Fig. 7 compares the measured loss with Norris ellipse at I_c degradation 58%. If mechanical load is uniformly applied to HTS tape, theory and measurement agree well because distribution of I_c is uniform. Therefore, we must apply Norris theory when critical current is uniform. Estimating characteristics of distribution of I_c, we have to compare AC loss measurement data to Norris theory. We speculate that this is caused by non-uniformity of the HTS tape, but the reason is not clarified yet.

3.2. AC loss of coated conductor by I_c degradation

Fig. 8 shows I_c of coated conductors in experiment. Measured I_c is 74 A. The constructions of coated conductor differently Bi-2223, which comprises multiple coatings on a base material, or substrate, is designed to achieve the highest degree of alignment possible of the atoms in the superconductor material. Therefore, the characteristic of I_c degradation of coated conductor is different from that of Bi-2223 tape. I_c degradation occur to a little at Bi-2223 tape due to composing of multi-filament for the Bi-2223 conductors. Fig. 9 shows I_c degradation percentage with respect to bending diameter. Coated conductor shows good characteristic in accordance with bending rate because thickness of YBCO is 1 μm. Also, I_c dose not decrease, when bending diameter is 10 mm. that means the mechanical characteristics of coated conductor is quietly different from that of Bi-2223, when coated conductor is bending from the center of gravity at neutral axis, tension of test sample is very small.

Fig. 10 shows the self filed loss of coated conductor tape the results means that the experimental results haven't related to the bending diameter. When bending diameter is more than 10 mm, critical current and self field loss hardly ever change. In other words, when I_c degradation dose not happen at the HTS tape, self field loss isn't obviously given the influence. Fig. 11 shows the Ac losses as a function of peak current in experiment. Coated conductor tape is composed of Nickel-tungsten alloy substrate, buffer materials which are Yttrium-Oxide, Yttrium-stabilized Zirconia, and Ceria, YBCO superconductor, Silver, and copper alloy stabilizer.

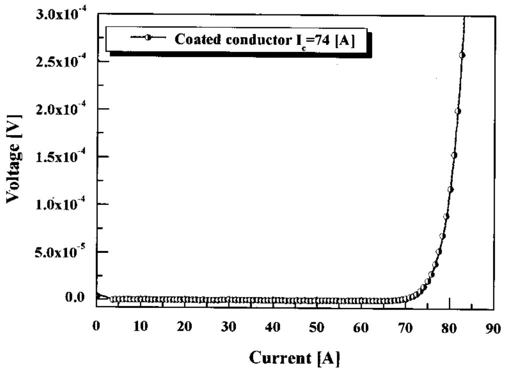

Fig. 8. Measurement of critical current.

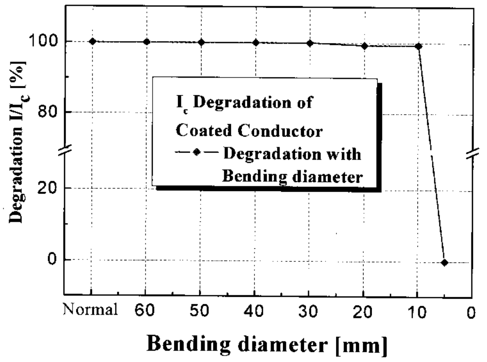

Fig. 9. I_c degradation of coated conductor with bending diameter.

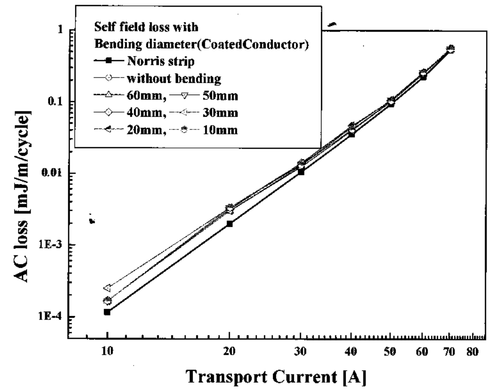

Fig. 10. Self-field loss of coated conductor with various bending diameter.

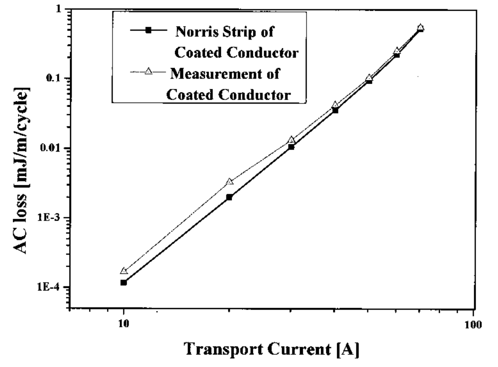

Fig. 11. Self-field loss compared Norris theory to measurement.

Because of B–H curve characteristics of the substrate (Nickel), self-field loss data of coated conductor is slightly different from Norris equation. When transport current is small, ferromagnetic loss of nickel has been affected to almost of the self field loss. However, when transport current of test sample is reached over the 30% I_c, ferromagnetic loss of nickel were saturated and the loss characteristics were similar to those of coated conductors with non-magnetic substrates. AC loss characteristic of coated conductor is mainly related to self-field loss. That is different from Norris equation due to B–H curve characteristics of the substrate (Nickel). It could be canceled out the affection of loss from the substrate based on Ni alloy, the experimental results is quiet similar to the results achieved from Norris equation.

4. CONCLUSION

This study is that knowledge of dependence of AC losses on stresses/strains of HTS conductors is important for AC power applications. The obtained results can be summarized as follows:

1. The result obtained in the study shows that the Norris ellipse model is not appropriate enough to explain the relationship between I_c and AC loss, when mechanical

deformation is involved. A superconducting tape with poorer uniformity in critical current has lower measured and calculated loss ratio than that with more uniform distribution. We speculate that this is caused by non-uniformity of the HTS tape, but the reason is not clarified yet. This means when we develop a new HTS tape, the transport current loss can be used as a rough indication of the uniformity.

2. AC loss of coated conductor tape is slightly different to the calculation value from Norris theory, because of the substrate with Ni-W5%. Owing to initiation region on the B-H domain of the substrate with Ni-W has higher hysteresis characteristics, the experimental result is carried out higher than the computation results from Norris strip theory.

3. The structure of coated conductor tape is different from the Bi-2223 conductor, and it is sharply thin thickness for the YBCO layer which is around 1 ㎛. When taking the bending strain for making coil structure, it is concluded that coated conductor tape exactly lost the superconductivity caused by cracking on the YBCO layer.

4. When coated conductor is bending from the center of gravity at neutral axis, tension of test sample is very small. i.e., the bending characteristic of coated conductor tape is quiet excellent Because of all layer thickness of coated conductor tape is very thin and its shape is given the effect to tension of superconducting layer.

ACKNOWLEDGMENT

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