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Comparison of Magnetization loss of YBCO wires and BSCCO Wires

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***Abstract*-- Multi-stacked HTS wires are needed to conduct large current in the power application. In this paper, magnetization losses of the multi-stacked YBCO wire and the BSCCO wire have been measured and compared. 4 types of YBCO wires and BSCCO wires, that is, single, 2-stacked, 3-stacked and 4-stacked, have been tested. HTS multi-stacked wires were fabricated using face-to-face type stacking method. Measurements of magnetization loss were performed under various angles of external magnetic field to consider the anisotropic characteristics of HTS wires. The ratios of the magnetization loss by multiple stacking of superconducting wires were presented. Measurements results show that loss ~~reduction~~ ratios have three distinct regions due to the magnitude of external magnetic field, the material of HTS wire and number of stacks.**

1. INTRODUCTION

The high temperature superconductor(HTS) has been developed very rapidly since the discovery of HTS with critical temperature of over 30K, and it was possible to make HTS wire using liquid nitrogen as the refrigerant. The HTS wire has been tried to be applied to the transformer, cable and fault current limiter. Coming soon are the days when the practical use of the superconductor spreads over a part of industry widely, but most of electric machines generate AC[1].

AC loss is very important parameter to design in the superconductor power machine of both of the first and second generation HTS wires. The studies of AC loss calculation methods and the ways to reduce losses have been run actively by scientists. There are many kinds of loss calculation and measurement methods, for example, the losses by different angle of external magnetic field on HTS wire, the losses by different multi-stacked wires used to increase current capacity of HTS wire, and the losses by the transport current under external magnetic field [2-6]. The second generation HTS wire usually has four layers : substrate layer, buffer layer, YBCO layer and protection layer with Ag unlike the first generation HTS wire fabricated with PIT method. Among these layers, the substrate layer and the protection layer are made of Ni or Ni-W alloy and Ag or Cu, respectively, and they affect losses in case of AC magnetic field. But the loss ratio of the YBCO wire to total loss decreases if AC magnetic field increases[7-9].

In this paper, we measured magnetization losses of the 1 ~ 4 multi stacked BSCCO wire and YBCO wire. The application angle of external magnetic field was varied to 90, 60, 45, 30° [2]. We compared the measured data of a single wire with the values calculated using strip model expression[10], and examined the dependence of magnetization loss of the multi-stacked first generation HTS wire and the second generation HTS wire.

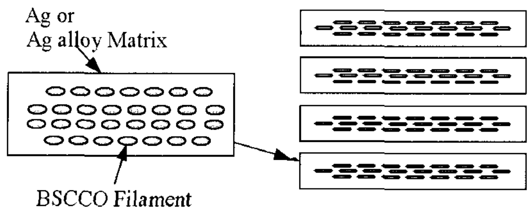
2. SET UP FOR MEASUREMENT

The structures of the multi-stacked wires and experimental set up for loss measurement are given in this section. Table I shows the specifications of the Bi-2223 wire and YBCO coated conductor. Width and thickness of the Bi-2223 wire were 4.1mm and 0.21mm, respectively. Critical current of the Bi-2223 wire was 125A. YBCO CC had the structure of a substrate layer, buffer layer, YBCO layer and Ag layer. The thickness of each layer were as follows; 1) substrate layer: 60 μm, 2) buffer layer: 2.04μm, 3)YBCO layer: 1μm, 4) Ag layer: 1.2μm.

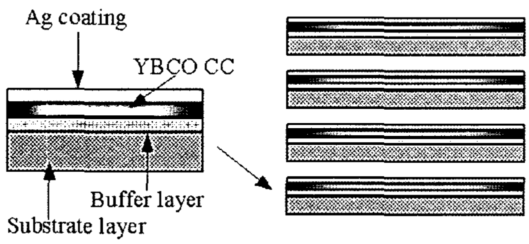
The cross-sections and stacked geometries of the multi-filamentary BSCCO wire and layer-structured YBCO CC are shown in Fig. 1. There is no air gap and no insulation material between each HTS wire. Fig.2 shows the external circuit diagram for measuring the magnetization loss. α in Fig. 2 stand for the angle of external magnetic field. *a* and *d* are the half width and thickness of HTS wires, respectively. The magnetization losses generated in the superconducting wires by the external magnetic field were measured by the linked-pickup-coil method.[2]

TABLE I
SPECIFICATIONS OF BI-2223 WIRE AND YBCO COATED CONDUCTOR

Bi-2223	Width	4.1mm
	Thickness	0.21mm
	Ic	125A at 77K 0T
YBCO COATED CONDUCTOR	Width	8 mm
	Ag layer	1.2 μm
	YBCO layer	1 μm
	Buffer layer	2.04 μm
	Substrate layer	60 μm
	Ic	166A at 77K 0T



a) BSCCO wire



b) YBCO wire

Fig.1. Cross-section and stacked geometry of Bi-2223 wire and YBCO CC.

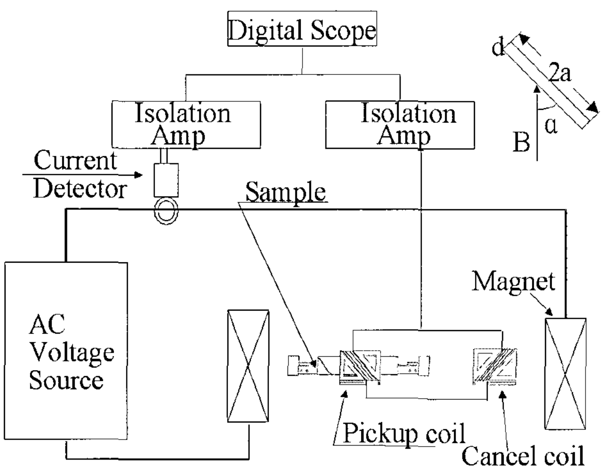


Fig. 2. Set up for loss measurement.

3. RESULTS OF MEASUREMENT

Measurement of magnetization losses in a single Bi-2223 wire and YBCO CC by the perpendicular external magnetic field was carried out first. Fig.3 shows the magnetization losses of Bi-2223 wire and YBCO CC. Analytic calculation of magnetization loss which was suggested by Brandt and Indenbom are also presented in Fig. 3.[3]

$$Q=\frac{4\mu_0 a^2 J_c dH}{S}\left[\frac{2}{\beta}ln(cosh\,\beta)-tanh\,\beta\right] \qquad (1)$$

where $\beta = H/H_c$, $H_c = J_c d/\pi$, a is the half width of the superconductor. J_c and d are critical current density and the thickness of the superconductor, respectively. Q and S are magnetization loss per unit volume and the surface of superconductor.

Filled and unfilled square symbols show the measured and the calculated loss of YBCO CC in Fig. 3, respectively. Filled and unfilled star symbol show the measured and the calculate loss of Bi-2223 wires, respectively. Calculated values and measured values of both wires agree well. Loss density of YBCO CC is about 100 times larger than that of the Bi-2223 wire near 0.1T of external magnetic field as shown in Fig. 3.

Measured magnetization losses by the perpendicular magnetic field of 4-stacked wires are given in Fig. 4. The filled symbols and the unfilled symbols are related to YBCO CC and Bi-2223 wires, respectively. Also the square, circles, triangles and star symbol shows the loss of a single, 2-stacked, 3-staked and 4-stacked wire, respectively. Fig. 4 shows that loss density per unit volume decreases for both YBCO CCs and BSCCO wires when number of wires used in the stack increases. Again, loss density of YBCO CC is over 100 times larger than that of Bi-2223 wires for all cases.

Magnetization losses of a single Bi-2223 wire and YBCO CC at various angle of external magnetic field are shown in Fig. 5. It is well known that most of the

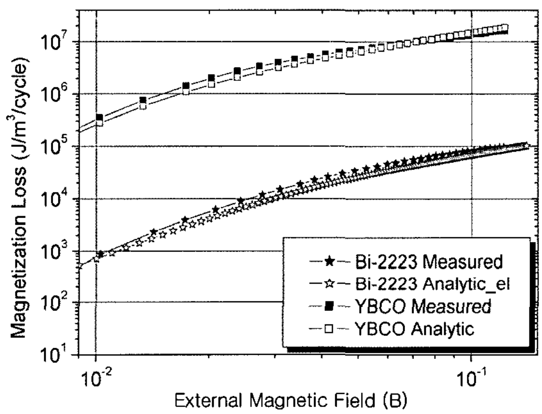


Fig. 3. Comparison of the magnetization losses of Bi-2223 wire and YBCO CC by perpendicular magnetic field.

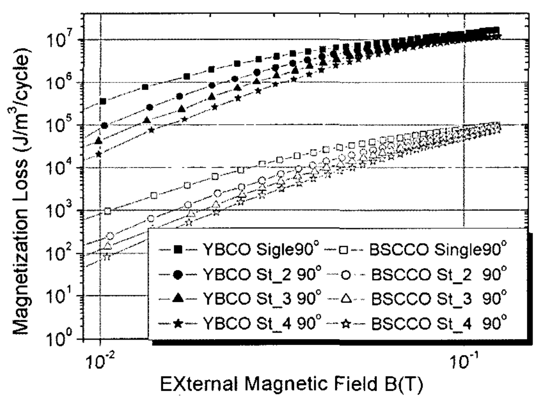


Fig. 4. Magnetization losses of a single Bi-2223 wire and YBCO CC at various angles of external magnetic field.

magnetization loss is generated by perpendicular magnetic field in HTS wires with high aspect ratio. But magnetization loss of 4-stacked YBCO with perpendicular magnetic field (Fig. 4) is almost the same as that of the YBCO wire with magnetic field of 30° (Fig. 5). It proves that stacked wires can considerably reduce the magnetization loss. Fig. 6 shows that the magnetization loss of the 4-stacked YBCO CC and Bi-2223 wire at various angles of external magnetic field.

In Fig.6, losses of the 4-stacked Bi-2223 wires increase almost straight. That is because the critical magnetic field, $B_c=\mu_0 J_c d/\pi$, of the 4-stacked Bi-2223 wire is so high that loss curves have not reached the knee point up to the external magnetic field of 0.12T. On the other hand, losses of the YBCO CCs have already reached the knee point, and those have begun to bend.

To examine the effectiveness of the multi-stack, it is useful to observe the loss ratio of the stacked wire and the single wire. In this paper, we observe the loss ratio, which are the ratio of loss at arbitrary angle to loss at 90°.

loss ratio = loss of arbitrary angle / loss of 90°

Loss ratio can be divided into three regions as in Fig. 7. In region I, external magnetic field, B_{ext}, of both wires, does not reach B_c. It means the rates of loss increment of both

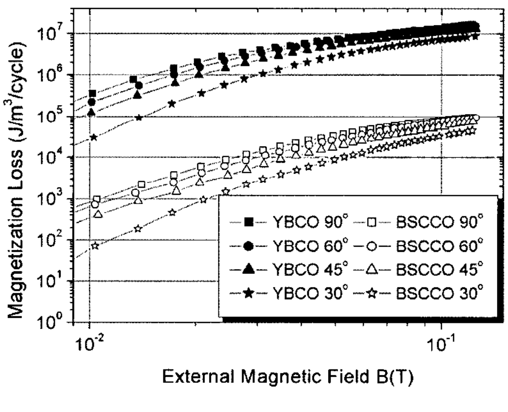


Fig. 5. Magnetization loss of single Bi-2223 wire and YBCO CC at various angles of external magnetic field.

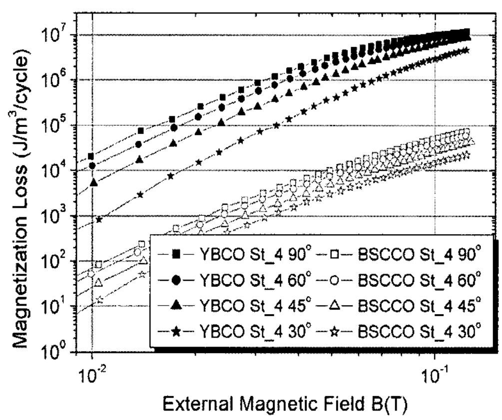


Fig. 6. Magnetization loss of 4-stacked Bi-2223 wire and YBCO CC at various angles of external magnetic field.

wires are almost the same, therefore, the loss ratio of the two samples is almost constant. Region I appears when B_{ext} is low.

In region II, B_{ext} of one wire exceeds the B_c, but B_{ext} of the other wire does not reach the B_c. Loss increment of the wire which exceeds the B_c is smaller than that of other wire which does not reach the B_c. The loss ratio of this case increases as the B_{ext} increases. Region II appears at medium level of B_{ext}.

B_{ext} of both wires exceed B_c in region III. When this happens, rate of loss increments of both wires are almost the same, therefore, the loss ratio becomes constant. Region III appears at high magnetic fields.

The knee point between the regions are determined by B_c, that is, number of stacks, material of superconducting wire, shape of the superconducting wire. Normalized loss ratios of single YBCO CC are given in Fig. 8, where losses are divided by the loss at 90°. Fig. 8 shows loss at 30° case(star symbol) begins to penetrate at about 0.01T and fully penetrated at about 0.08T. Therefore, loss ratio increases between 0.01T and 0.08T. Losses of 90° and 30° complete full penetration at above 0.08T, therefore, loss ratio of 30° case almost levels off at above 0.08T. Fig. 8 shows the loss pattern of region II and region III in Fig. 7.

More magnetic field is needed to fully penetrate Bi-2223 wire than YBCO CC. No cases have finished the full penetration process between 0.01T and 0.12T in Fig. 9. In addition to the higher magnetic field for full penetration, full penetration process of Bi-2223 wires need much wider magnetic field span than that of the YBCO CC. Although full penetration processes of Bi-2223 wires are under way in all cases of Fig. 9, 90° case is the fastest. So loss ratios increase continuously for all cases. Bi-2223 shows longer full penetration process (Fig. 9) than that of YBCO CC (Fig. 8) because Bi-2223 has lower n-value. Fig. 9 shows the loss pattern of region II in Fig. 7.

For 4-stacked YBCO CC, higher magnetic field and wider magnetic field interval is need for full penetration than single YBCO CC. As is shown in Fig. 10, loss ratios increase continuously for all cases because full penetration processes are under way. Fig. 10 shows the loss pattern of region II in Fig. 7.

No cases have begun full penetration process yet in Fig.11 because the B_c of the 4-stacked Bi-2223 wires is high. Therefore the loss ratio levels off between 0.01T and 0.12T. Fig. 11 shows the loss pattern of region I in Fig. 7.

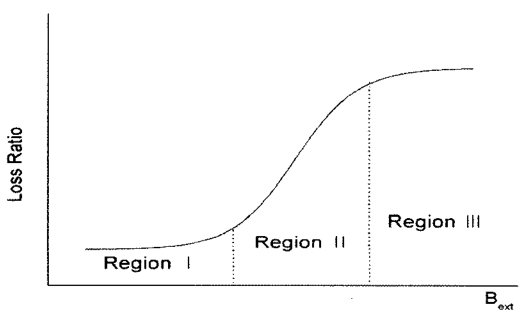


Fig. 7. Pattern of loss ratio versus B_{ext}.

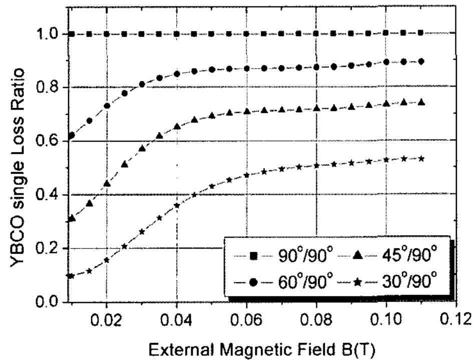


Fig. 8. Loss ratio (θ°/90°) of single YBCO CCs.

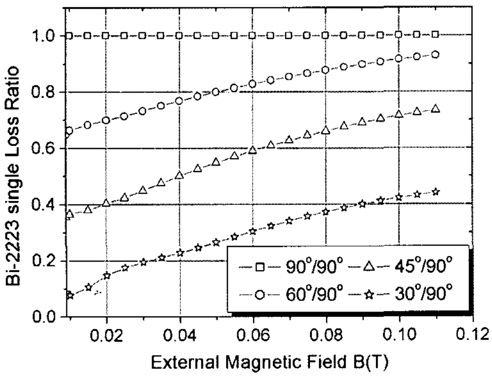


Fig. 9. Loss ratio (θ°/90°) of single Bi-2223 wires.

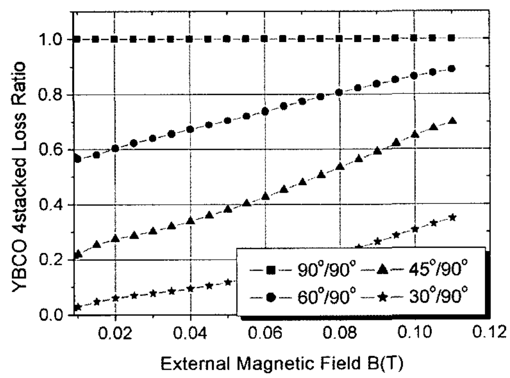


Fig. 10. Loss ratio (θ°/90°) of 4-stacked YBCO CCs.

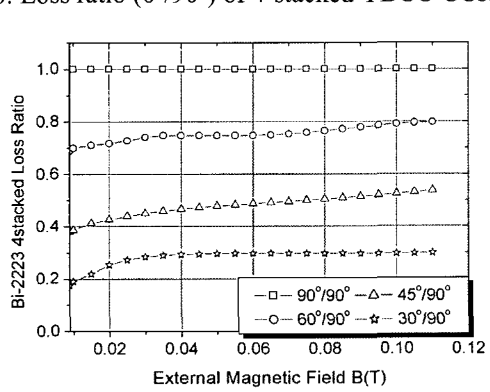


Fig. 11. Loss ratio (θ°/90°) of 4-stacked Bi-2223 wires.

4. CONCLUSION

Magnetization losses in the Bi-2223 wires and the YBCO CCs were measured and compared. 4 types of stacked wire including single wire were tested. Loss ratio showed three different regions according to their penetration status. As the external magnetic increases, loss ratio levels off first, then increases and levels off again.

The knee point between each region depends on material of superconducting wire, angle of external magnetic field and number of stacks. Loss ratio is helpful for us to understand the mechanism of loss reduction process and to evaluate the amount of loss reduction at a given external magnetic field.

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