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Effects of the External Magnetic Field on the Critical Current and AC Loss of HTS Stacked Tapes

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Abstract -- **According to the improvement of the HTS wires performance, several types of HTS superconducting machines are being developed. Stacked HTS tapes are used to conduct the current of the HTS power machines. To develop the HTS power machines, the critical current characteristics of a stacked HTS tapes in external field need be examined. In this paper, we present effect of the external magnetic field on the critical current of HTS stacked tapes. The critical current of various kinds of multi-stacked HTS tapes in external magnetic filed are compare with that of a single HTS tape. Test results show that critical current of single HTS tape is smaller than that of multi-stacked HTS tape in the external field.**

1. INTRODUCTION

Superconducting power applications, such as, transformer, motor, current limiter, and transmission cable, are being developed. Critical current of a HTS tape is not enough to conduct the large current to the power machines. Furthermore, the critical current of HTS tapes that are used in power machines decreases due to the strong external magnetic field.

One method to conduct the large current of the HTS power machines is lowering the operating temperature using the cryocooler. Another method is using the multi-stacked tapes. Performances of the multi-stacked tape including critical current and ac losses are not the same as the simple multiplication of the single tape. Accordingly, characteristics of the multi-stacked tapes should be carefully examined.[1]

This paper described characteristics of HTS 4-stacked tapes. The critical current of the 4-stacked HTS tapes was compare with that of the single HTS tape in external magnetic filed. Various directions of external magnetic field were applied to the multi-stacked tape. Self-field loss of the single HTS tape and 4-stacked tapes were also measured.

2. CRITICAL CURRENT OF A SINGLE TAPE

BSCCO-2223 tape was used in this experiment because it has been the most widely used HTS tape in HTS power machines.

Critical current of the HTS tapes that was used for the stacked tapes was 74A at 77K. Width and height of the tape were 3.1mm and 0.16mm, respectively. Specifications of the HTS tape are given in Table 1.

TABLE I
SPECIFICATIONS OF HTS(BI-2223) TAPE

Material	BSCCO-2223
With	3.1 mm
Height	0.16 mm
Matrix	Ag alloy
Twist	No
Critical Current	74 A, 77K
Max stress (77k)	85 Mpa
Max strain	0.15%

Critical current of single HTS tape were measured and compared with that of multi-stacked HTS tapes. External magnetic field was applied using the iron core magnet with air gap. Fig. 1 shows the sample multi-stacked taped which was located in the air gap of the magnet. Inhomogeneity of the magnetic field which was applied to the multi-stacked sample was less than 4%. To apply the magnetic field with various direction, the sample was made to be rotated in the air gap.

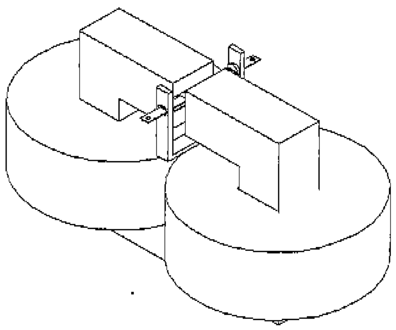


Fig. 1. HTS sample in the air gap of the magnet

Fig. 2 shows the relation between the magnet current and the generated magnetic field by the iron core magnet which was shown in Fig. 1. Fig. 2 shows that magnetic flux density begins to saturate at above 250mT.

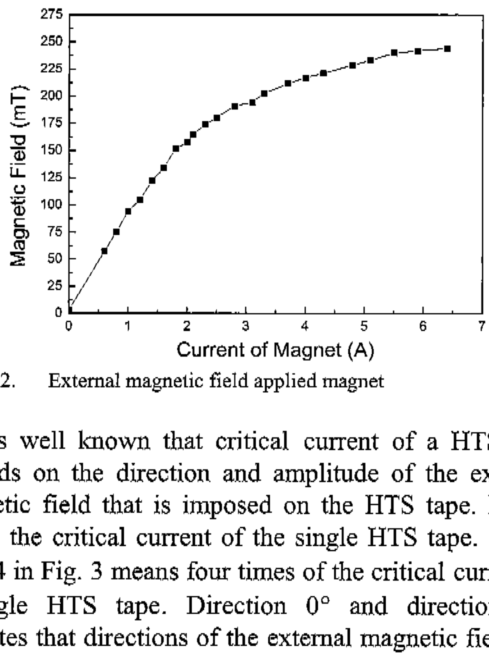
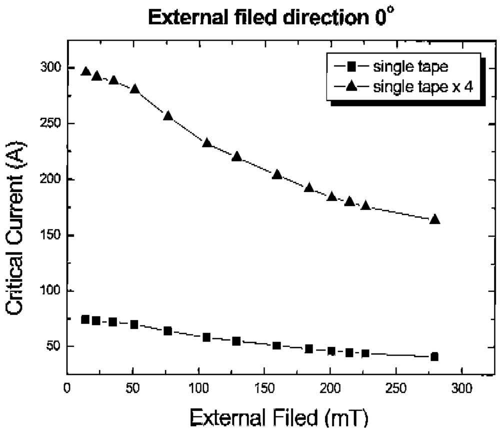
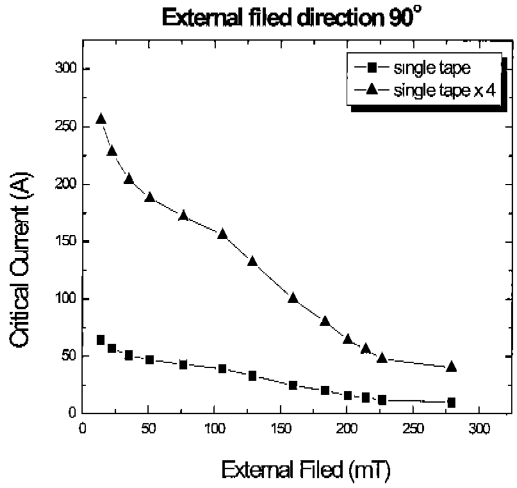


Fig. 2. External magnetic field applied magnet

It is well known that critical current of a HTS tape depends on the direction and amplitude of the external magnetic field that is imposed on the HTS tape. Fig. 3 shows the critical current of the single HTS tape. Single tape×4 in Fig. 3 means four times of the critical current of a single HTS tape. Direction 0° and direction 90° indicates that directions of the external magnetic field are parallel and perpendicular to the tape, respectively.



(a)



(b)

Fig. 3. I_c-B curves of single HTS tape with different angles of external magnetic field (a) parallel (b) perpendicular

Standard criterion of 1(μV/cm) was applied to determine the critical current.

As the magnetic field increased from the parallel direction to the perpendicular direction, critical current decreases rapidly as in Fig. 3. Especially, when external magnetic field of perpendicular direction was applied, critical current decreases sharply in low magnetic field. When 120mT was applied, critical current of HTS tape dropped by 1/2.

3. Critical Currents of Stacked Tape

To examine the characteristic of a multi-stacked tape, 4 HTS tapes were stacked. Three different samples of 4-staked tape were prepared. No insulation between the tapes was made in the first sample. In the second sample, insulation with Kapton film of 55μm was placed between the tapes in order to prevent coupling among the tapes. In the last sample, each tape was separated by 0.3mm and was not insulated.

Structure of the stacked HTS tapes and current leads are shown in Fig. 4. Total length of sample was 170mm and the distance between two voltage taps was 120mm.

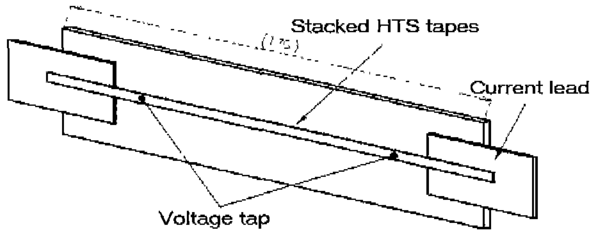


Fig. 4. Structure of the multi-stacked sample

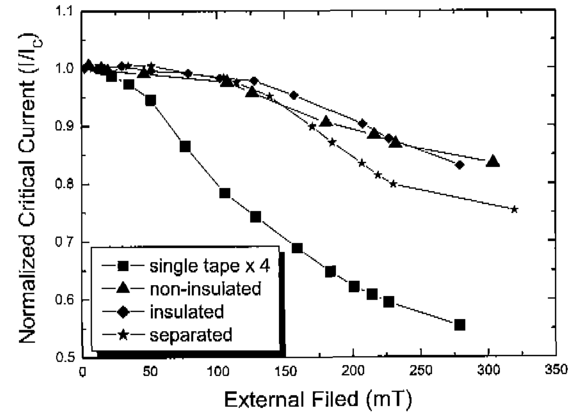
When there were no external magnetic fields, critical current of the non-insulated, the insulated, the separated sample were 221A, 236A, and 247A, respectively. Critical current of the separated sample was the highest among the three samples. Even the separated sample which had the highest critical current, the critical current of the 4-stacked tape was much smaller than that of the 4 times of the single tapes, 296A. It was due to the effect of the self-field which was generated by neighboring tapes. Another reason of the decrement of the critical current was deterioration of the multi-staked sample which was caused during the fabrication of the sample.

Variation of the critical current of three 4-stacked HTS tapes is shown in Fig. 5. Normalized critical current (I/I_{co}) was adopted because critical current of each stacked HTS sample was different. I and I_{co} stand for critical current in external magnetic field and critical current in self-field, respectively.

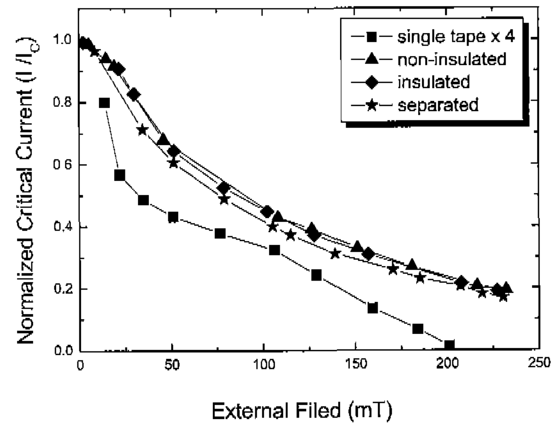
It can seen in Fig. 5 that critical current of the multi-stacked tapes decreases more at the perpendicular magnetic field than the parallel magnetic field, which was the same tendency with the single tape. When the parallel magnetic field of 100mT was applied, critical current of single tapes was only 78% of that of the 4-staked tapes. It was quite different results from our expectation. We expected the critical current of the single tapes would be larger than those of the multi-stacked tapes.

The reason of this experimental result was that outer HTS tapes prevented the magnetic field from penetrating into the inner HTS tapes. In a single tape, external magnetic field penetrated the whole tapes. In multi-stacked tapes, only small portion of the external magnetic field penetrated the inner tapes. The other reason was that pinning force increased because the flux had to pass four HTS tapes. More strong magnetic fields was required to move the four vortex simultaneously. The critical current of the separated stack was the smallest among the multi-stacked because magnetic field could contact the sample through the space between the tape.

In case of the perpendicular magnetic field, we got the same tendency as the parallel case, that is, critical currents of the stacked tapes were larger than that of the single tapes. But difference between the critical currents reduced. The reason that the critical current of the multi-stacked tapes were larger than that of the single tape was the same with the parallel magnetic field.



(a)



(b)

Fig. 5. Normalized critical current of Bi-2223 stacked superconducting as external magnetic filed for (a) parallel (b) perpendicular

4. SELF-FIELD LOSSES OF STACKED TAPE

When we use stacked HTS tapes in electric power machines, AC loss is one of the major concern. Self-field loss of the single tape and the multi-stacked tapes were measured.

Transport current in a superconductor generates a magnetic self-field around the conductor. During each current cycle the self-field partially penetrates the superconductor and therefore cause hysteresis type loss that called the self-field loss. If there is no alternating magnetic field other then the self-field, the loss per cycle per volume in a superconductor with an elliptical cross-section is given by Norris equation.[2]

$$P(F) = \left(\frac{\mu_0 I_c^2}{\pi}\right)\left[(1-F)\ln(1-F) + (2-F)\frac{F}{2}\right]$$

where $F=I_c/I_p$, I_c and I_p are critical current and peak value of AC current.

Fig. 6 shows the measured self-field loss of the single tapes and calculated self-field loss by using the Norris equation.

Although the measured value was a little small at small current region, two losses agreed well at above 30A.

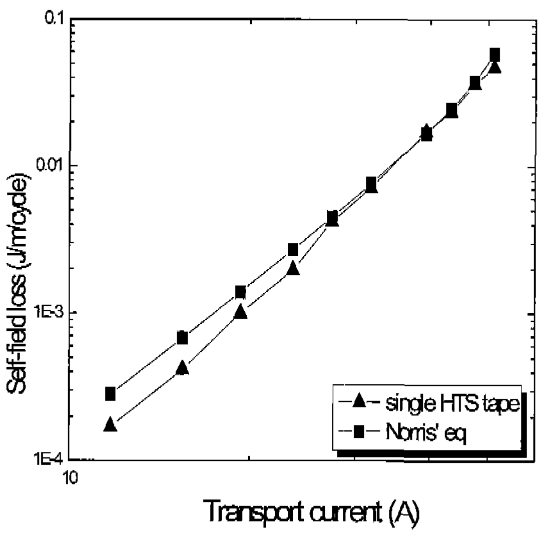
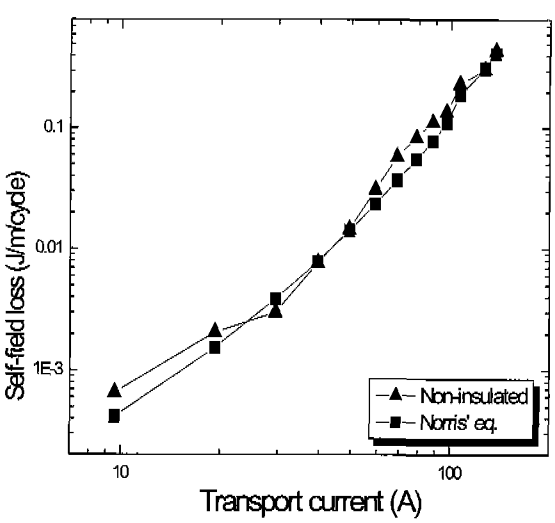
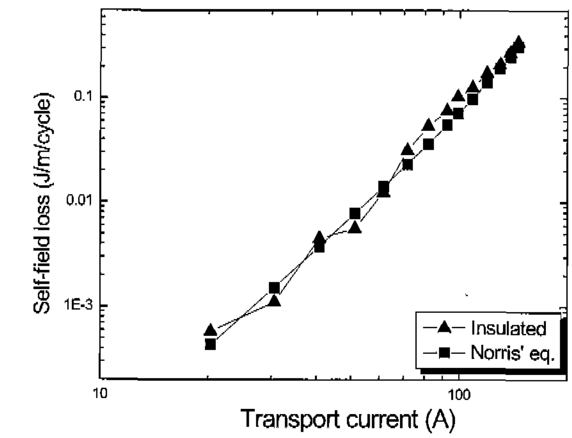


Fig. 6. Self-filed loss by Norris equation and single HTS tape

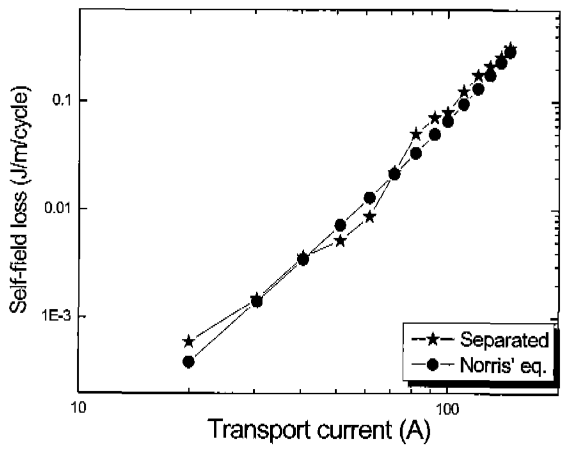
Self-filed loss of the insulated, non-insulated and the separated HTS tape are given in Fig. 7. At higher current, measured losses of the three samples were a little larger than the losses of calculated loss by using Norris equation. Measured results generally agreed well with the calculated value.



(a) Non-insulated multi-stacked tape



(b) Insulated multi-stacked tape



(c) Separated multi-stacked tape

Fig. 6. Self-filed loss by Norris equation and stacked HTS tape

Table II shows the comparison of the AC losses of the multi-stacked sample. AC loss of the separated sample was about 70% of the non-insulated sample and 60% of the insulated sample. Main reason of this difference was the difference of the critical current. AC loss depends on the critical current. Critical current of the separated sample was the largest and that of the non-insulated sample was the smallest. It was meaningless to compare the AC loss of the multi-stacked sample with that of the single tapes because the current and the critical current of the samples were quite different.

TABLE II
COMPARISON OF THE AC LOSSES OF THE MULTI-STACKED SAMPLES

Sample	Current A	Measured J/m/cycle	Calculated J/m/cycle
Non-insulated	137	0.44	0.41
Insulated	138	0.27	0.25
Separated	147	0.31	0.29

5. CONCLUSIONS

This paper described characteristics of HTS 4-stacked tapes. The critical current of 4-stacked HTS tapes were compare with that of a single HTS tape in external magnetic filed. Effect of the direction of the external magnetic field was considered in this paper.

According to the measurements, Critical current of the single tape at self-field was the largest among the four samples. Critical current of the separated multi-stacked samples at self-field were larger than those of the non-insulated and the insulated sample tape.

But in the external field, critical current of the single tapes is the smallest among the four tapes. The reasons of this result were that magnetic shielding by the outer HTS tapes and the stronger pinning force which was the sum of each tape's pinning force.

AC losses of the four samples were measured and compared with the calculated loss by using Norris equation. Measured results generally agreed well with the calculated value. This implies that AC loss of the multi-stacked samples can be measured by using the same method with the single tape.

ACKNOWLEDGMENT

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