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A Study on the Characteristic Evaluation of An HTS Coil with respect to the Winding Methods

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***Abstract*-- In superconducting magnet applications, winding methods of the superconducting magnet can be classified into a layer winding and a pancake winding. The superconducting magnet using high temperature superconductor (HTS) with rectangular shape is generally fabricated using the pancake winding method. On the other hand, low temperature superconducting (LTS) magnet may be wound by either a pancake winding or a layer winding. Compared with the layer winding, the pancake winding method has a merit of easy replacement of a damaged pancake module, but it also has a demerit of requirement of splicing between each double pancake modules. In this paper, we investigated characteristics of the layer and pancake winding methods using HTS. Six samples were wound out of BSCCO and Coated Conductors (CCs) by two winding methods and their characteristics were experimentally observed.**

1. INTRODUCTION

In recent superconducting applications, superconducting wire is widely used in various winding methods on their purpose [1-3]. The winding method for the superconducting magnet can be classified into a pancake winding and a layer winding. In case of the pancake winding, each pancake module is fabricated individually and then they are assembled together to make a magnet. It has the advantage of convenience to replace damaged one when a pancake module is damaged from some thermal or mechanical disturbances. However, the necessity of joints to connect each pancake module can make it difficult to sustain a persistent current in the magnet. Joints of the magnet are formed in process of soldering between copper terminal and a wire as well as between wires. On the other hand, if a magnet is wound by the layer winding using one piece wire, the joint can be fewer than that of a magnet wound by pancake winding. However, in this method, it is impossible to replace damaged parts to new one. In general, low Temperature Superconducting (LTS) magnets are wound with either the layer winding or the pancake winding methods. In the manufacture of High Temperature Superconducting (HTS) magnet, the pancake winding is used more than the layer winding because HTS wire have features of thin and rectangular shape.

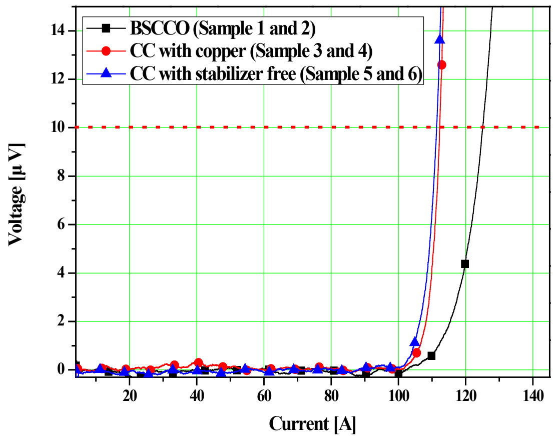

Fig. 1. *V-I* curve graph of BSCCO, CC with stabilizer and CC without stabilizer wires.

TABLE I
SPECIFICATIONS OF HTS WIRES.

Pancake Layer	Sample 1 Sample 2	Sample 3 Sample 4	Sample 5 Sample 6
Manufacturer	American Superconductor	SuNAM	SuperPower
HTS wire	BSCCO	CC	CC
Width	4.2 mm	4 mm	4 mm
Thickness	0.26 mm	0.1 mm	0.055 mm
Stabilizer	Stainless Steel	Copper	-
Critical bend diameter	38 mm	Not Reported	11 mm
Substrate	-	Hastelloy	Hastelloy
Critical Current @ 77 K	125 A	112 A	111 A

In the layer winding HTS magnet, it is reported that particular attention has to be paid at the end turns of the windings in order to achieve proper transition from one layer to another [4]. However, considering requirements of magnetic field homogeneity, and the tolerances in both HTS wire dimension and insulation thickness variation, the

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layer winding can be chosen rather than the pancake winding method for HTS magnets [5, 6]. Moreover, as we mentioned before, the layer winding can have a smaller joint resistance when using a long piece of HTS.

In this paper, a layer winding method for HTS wire was proposed and samples using pancake and layer winding method were fabricated and tested to verity the feasibility of the layer winding. Three kinds of HTS were used to fabricate samples and characteristics of two winding types were compared by the results of critical current test. In addition to this, over-current tests were performed to observe the probable damage problem of the wires.

2. FABRICATIONS OF SAMPLES

2.1. Specifications of HTS wires

Three kinds of wires, BSCCO, coated conductor (CC) with stabilizer and CC without stabilizer were used and six samples were fabricated.

The specifications of the HTS wires using each sample are shown in Table I. Fig. 1 shows *V-I* characteristics of HTS wires in liquid nitrogen. The 4-probe method was applied to the measurements of a critical current and 1 μV/cm criterion was used for determining quench. The critical currents of BSCCO, CC with stabilizer and CC without stabilizer were 125 A, 122 A and 111 A, respectively. Kapton tapes (width: 4 mm, thickness: 0.05 mm) were used for insulations of wires.

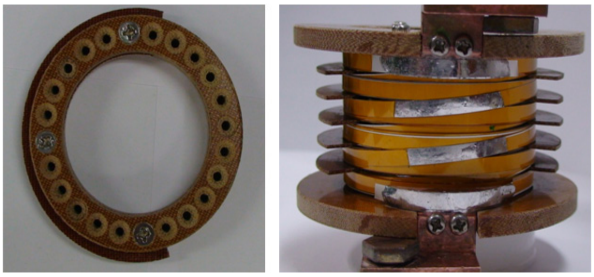

(a) (b)

Fig. 2. Photographs of (a) one double-pancake bobbin and (b) fabricated pancake winding sample.

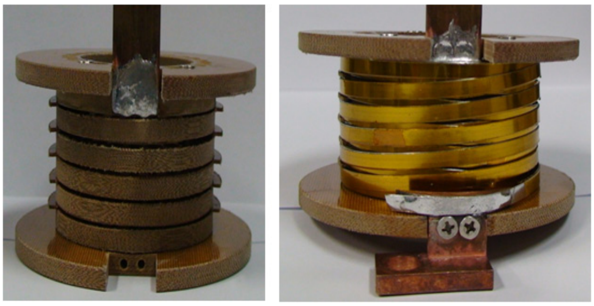

(a) (b)

Fig. 3. Photographs of (a) layer winding bobbin and (b) fabricated layer winding sample.

TABLE II
SPECIFICATIONS OF THE SAMPLES WITH PANCAKE WINDING.

Parameters	Sample 1	Sample 3	Sample 5
Conductor	BSCCO	CC with stabilizer	CC w/o stabilizer
Inner diameter	60 mm		
Outer diameter	63.6 mm	62 mm	61.55 mm
Total height	37 mm		
# of DP modules	3		
Height per DP	11 mm		
Turn per DP (SP)	10 (5)		
Total wire length	5.94 m		
# of DP splices	2		
Inductance	~50 μH		

2.2. Fabrication of pancake winding samples

Fig. 2(a) shows the double-pancake (DP) bobbin. Inner diameter and height of the bobbin are 60 mm and 11 mm, respectively. The critical bend diameter of the BSCCO and the CC without stabilizer is 38 mm and 11 mm, respectively [7, 8]. The critical bend diameter is the smallest diameter to which the wire can be wound without damaging the wire [9]. However, the critical bend diameter of the CC used to the SuNAM wire is not yet reported. The ReBCO layer points outward to winding curvature. DP bobbin consists of two number of single pancake bobbins with 4.5 mm per height of one and a spacer with thickness of 2 mm. Three double pancake modules were assembled to make one sample magnet. There are total four joint parts. Two joint parts are between copper current leads and the sample magnet and others are between the DP modules. The spacer with thickness of 2 mm was inserted among double pancake modules. The overlapped joint between wires was 3 cm long. The total height of the sample is 37 mm. Fig. 2(b) shows the fabricated sample. Specifications of pancake winding sample were shown in the Table II.

2.3. Fabrication of layer winding samples

In the layer winding method, turn is defined in an axial way while layer in a radial way. Fig. 3(a) shows the bobbin and a layer-wound sample coil. As shown in Fig. 3(a), it consists of six 4.5 mm long single bobbins with five 2 mm thick spacers. Therefore, both the layer winding and the pancake winding have the same height of 37 mm. Winding path of a layer magnet was composed of horizontal one sustained by the spacer and oblique one for the turn-to-turn transfer at a six degree angle range. The number of turns and layers are 6 and 5, respectively. In the process of winding, we focused three key issues:

1) As shown in Fig. 3, the first layer was joined on the inner copper terminal, and then the other layers is wound around the first layer and the inner copper terminal. To reduce the damage on the overlapped part with the other layers, soldering thickness should be as thin as possible between the inner copper terminal and the first turn of the first layer.
2) A damage of the HTS wire by an edge of a spacer should not occur when the wire is wound from one

TABLE III
SPECIFICATIONS OF THE SAMPLE WITH LAYER WINDING.

Parameters	Sample 2	Sample 4	Sample 6
Conductor	BSCCO CC	CC with stabilizer	w/o stabilizer
Inner diameter	60 mm		
Outer diameter	63.6 mm	62 mm	61.55 mm
Total height	37 mm		
# of turns per layer	6		
# of layers	5		
Total wire length	5.88 m		
# of joints between layers	-		
Inductance	~50 µH		

turn to another.

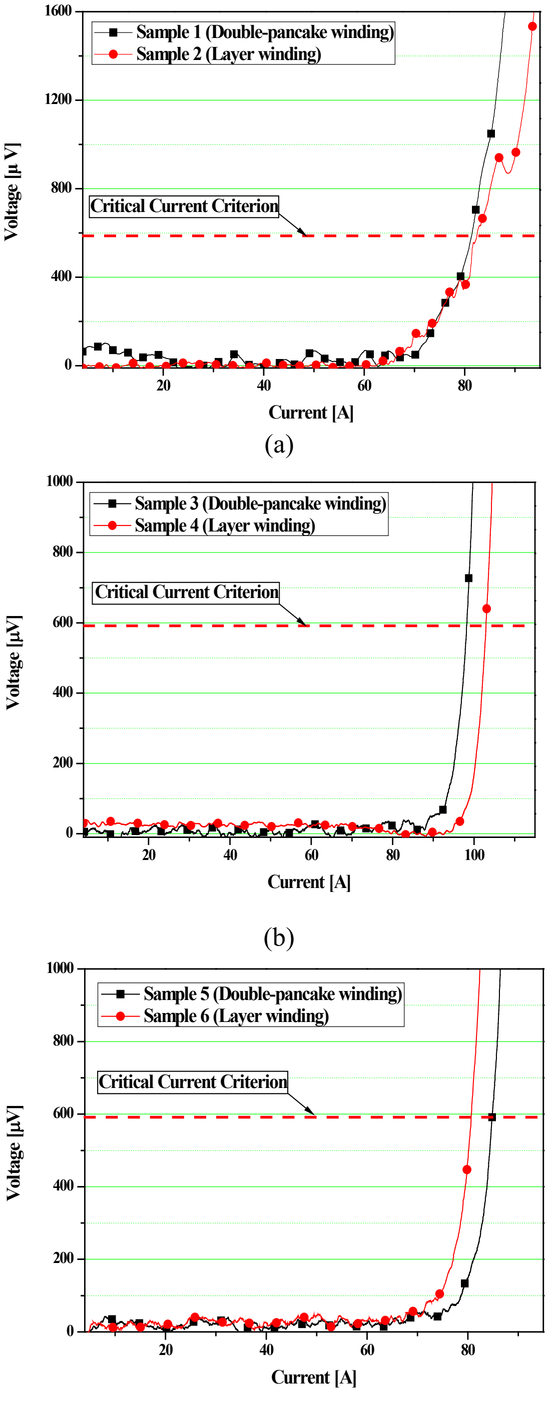
3) There is a gap between the height of the single layer bobbin and the width of the wire, 4.5 mm and4-4.2 mm, respectively. This gap essentially enables the layer winding to have an oblique winding angle in transition between each turn.

We fabricated the Sample 2, Sample 4 and Sample 6 with careful treatments mentioned above. Fig. 3(b) shows one sample fabricated by the layer winding. Specifications of layer winding samples were shown in the Table III.

3. EXPERIMENT AND DISCUSSION

3.1. The test of the critical current

Fig. 4 shows the measured voltage-current (*V-I*) curves of each sample and the critical current criterion was plotted using dot line. The experimental results of the Sample 1 and Sample 2 using the BSCCO are shown in Fig. 4 (a). The critical current of Sample 1 and Sample 2 are 81 A and 82 A, respectively. As shown in Fig. 4(a), the *V-I* curve of the Sample 2 looks unstable. So, tests were repeatedly carried out but these results were similar. Although the voltage looks unstable right after the sample reaches its critical current, it is estimated that the *V-I* curve is stable below the voltage of 1 µV/cm criterion Fig. 4 (b) shows the experimental results of Sample 3 and Sample 4 using CC with copper stabilizer. The critical current of Sample 3 and Sample 4 are 98 A and 103 A, respectively. The experimental results show that the critical current of Sample 4 is a little bit higher than that of Sample 3. Fig. 4 (c) shows the experimental results of the Sample 5 and Sample 6 using CC without stabilizer. These critical current are 84 A and 81 A, respectively. These results show that the critical current of the Sample 6 is a little bit lower than that of the Sample 5. The results of the critical current are shown in Table IV. The sample bobbin in this test was fabricated considering the critical bend diameter of wires. As shown in Table IV, the critical current of other samples, except Sample 3 and Sample 4, is higher than that of each wire. Although inner diameters of samples are larger than the minimum double bending diameter of each wire, the peak bending strain of Sample 1 and Sample 2, calculated as 0.43 %, is larger than a typical tensile strain limit of BSCCO wire, 0.4 %. Therefore, it was expected that the critical current degradation of Sample 1 and Sample 2 may be appeared by the influence of the small bending diameter. The CC wire used to Sample 5 and Sample 6 has no metallic stabilizer and is covered with silver layer. This wire should be under careful treatment because mechanical damage on a silver layer can be occurred by reasons such as micro scratch and tension. For this reason, it is thought that the critical current degradation of Sample 5 and Sample 6 was figured out a little bit high.



(a)

(b)

(c)

Fig. 4. Experimental results of (a) Sample 1 and 2, (b) Sample 3 and 4, and (c) Sample 5 and 6.

TABLE IV
CRITICAL CURRENT TEST RESULTS OF EACH SAMPLE.

	I_{C_SAMPLE}	I_{C_SAMPLE}/I_{C_WIRE}
Sample 1	81 A	0.65
Sample 2	82 A	0.66
Sample 3	98 A	0.88
Sample 4	103 A	0.92
Sample 5	84 A	0.76
Sample 6	81 A	0.73

TABLE V
OVER-CURRENT TEST RESULTS OF EACH SAMPLE.

	$I_{over\text{-}current}$	$I_{over\text{-}current}/I_{c\_sample}$
Sample 1	170 A	2.09
Sample 2	190 A	2.31
Sample 3	105 A	1.07
Sample 4	120 A	1.16
Sample 5	90 A	1.07
Sample 6	90 A	1.11

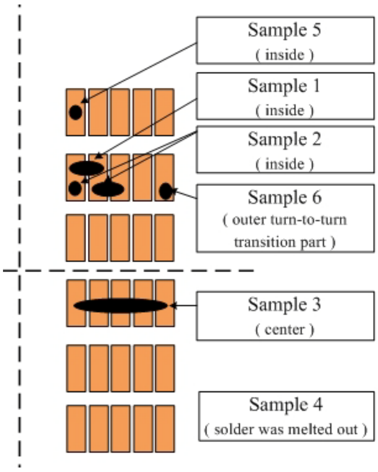


Fig. 5. Cross-sectional schematics of the sample with each damage spot marked.

In this test, critical currents of the samples with respect to two winding methods are different, but the difference between these values may be considered very small and no tendencies. These results can mean that the layer winding compared to the pancake winding has no problem in consideration to the critical current.

3.2. Over-current test

In process of the layer winding, mechanical damage of the wire at the end of the turn can be occurred because the winding direction of the wire is changed up and down. To check the probability of the damage on the layer-to-layer region, the over-current test was conducted until the samples were damaged. Current over the critical current was increased for 20 seconds and lasted for 1 minute until the sample seems to be damaged. The applied current was increased by 5 A in each test.

Fig. 5 shows the cross-section schematics of the damaged region of each sample. All the samples were damaged on local spot except Sample 4. The damage in Sample 1, Sample 2, and Sample 5 was found on the local spot of innermost wire. Sample 3 is observed that all of the turns wound in a radial direction got damaged. The damage in Sample 6 was occurred from the wire of the outermost turn-to-turn region. In case of Sample 4, it was observed that solder between copper stabilizer and ReBCO layer was melted out. Sample 4 was observed that solder layer between copper stabilizer and brass was melted down along the longitudinal direction. The HTS wire for Sample 3 and Sample 4 had two stabilizing layers, electroplated copper layer and soldered brass layer above the copper layer. There was no obvious tendency of damaged region in this test. However, it can be conformed that the damaged region has higher chance of arising in the innermost region, as Sample 1, Sample 2, and Sample 5, than other regions.

Table V shows test results of each sample in the over-current test. In the aspect of stability, Sample 1 and Sample 2, using BSCCO wire, was the highest. The reason is that BSCCO has larger heat capacity, thickness, and low resistivity compared with the other wires. On the other hand, the stability of Sample 5 and Sample 7, using CC without stabilizer, was the lowest. The damage is caused by some reasons such as external magnetic field, mechanical strain, and wire's non-uniformity critical current. In this test, the damage of the layer-to-layer transition region, we were concerned, was not found. There is little difference between pancake winding and layer winding using same wire. It was experimentally conformed that the layer winding will be possible to be applied the HTS magnet without major winding problems. However, since the samples used in the test were small coils, additional test for large magnet with high magnetic field or high magnetic stress is needed.

4. CONCLUSION

In this paper, we investigated the feasibility of the layer winding using HTS. Six samples using two kinds of winding methods were fabricated. The critical current tests and the over-current tests were performed to know the electrical characteristics of samples with each winding method. From the results of the critical current test and the over-current test, it is learned that the critical current was not affected by two winding methods. The damage of each sample was occurred at different location, but the problem was not observed when wound by the layer winding method.

From this research, we can verify the possibility of the layer winding method to apply HTS magnet. However, further researches such as magnetic field uniformity, mechanical stress, the effect of winding tension and epoxy resin should be progressed to verify the reliability for the layer winding method.

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