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Wind-and-flip technique for the fabrication of a persistent mode superconductive magnet by using a coated conductor

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Abstract-- **Persistent mode HTS pancake coil has been fabricated using a coated conductor by a "wind-and-flip" method. A coated conductor with the length of 1.2 meters was divided at the center along the length. The sliced coated conductor was wound on a pair of bobbins with a diameter of around 4 cm and two pancake coils connected superconductively without a resistive joint were prepared. By flipping one of the pancake coils, the magnetic field generated by each coil is to be aligned to the same direction and generate meaningful magnetic field while the magnetic fields of two spit coils are canceled without flipping. Permanent current was induced by flowing current to the coil immersed in liquid nitrogen pool using a power supply. A magnetic field of 48.8 Gauss was generated when 20 A of current was flowing in the pancake coils. The "Wind and flip" method can be applied for the fabrication of a long solenoid magnet by winding a sliced coated conductor on a cylindrical bobbin. It is also introduced that the construction of multiple sets of pancake (or solenoid) coils is possible by a "wind-and-flip" method using a wide coated conductor.**

1. INTRODUCTION

Since the discovery of high temperature superconductor (HTS), intensive researches have been carried out in order to apply these materials for the development of superconducting devices. Superconductive joining is a key technique for the construction of a persistent mode magnet that is essential for the superconducting devices operating at a stable and precise magnetic field. For instance, magnetic resonance imaging (MRI) requires a stable and precise magnetic field in order to obtain reliable information from the objectives being examined.

In order to fabricate a persistent mode magnet, the terminals of a superconducting wire should be joined superconductively. In case of conventional metallic superconductor such as NbTi, the filaments of NbTi exposed from Cu matrix are joined mechanically by pressing NbTi tube wherein NbTi filaments are inserted. By this simple technique, conventional superconductors such as NbTi are currently used to fabricate persistent coils for the MRI and laboratory magnets. However, a simple technique of mechanical joining cannot be directly applied for joining HTS oxide superconductors due to their brittleness. Therefore, another robust technique should be developed in order to use HTS materials for MRI and laboratory magnet applications. In case of Ag/BSCCO HTS wire, a thermomechanical method has been developed and superconductive joining has been successfully demonstrated [1-2]. But it requires a annealing at high temperature in order to make superconductive joining and therefore wide uses of Ag/BSCCO tape for the practical application has been limited due to the restriction of this technique in a certain application .

Coated conductor, which is consisted of stacks of epitaxial thin films on metallic substrate, shows better current carrying capacity under high magnetic field and is considered to be less expensive than Ag/Bi-2223 tape. Therefore many researches have been conducted for the use of coated conductor in the power devices such as motor, power transmission cable, fault current limiter, transformer, and prototype devices have been demonstrated. Until now, joining technique for coated conductor, which is a prerequisite for achieving a persistent current, has not been developed yet except some researches on the joint of coated conductor through silver stabilized layer [3] or ordinary Sn-Pb solder [4], which didn't accomplish the perfect superconducting joint between two coated conductors. Therefore, little research has been made for the application of coated conductor on magnet for MRI, NMR, magnetic separation and laboratory use. Very recently, Lee et al. [5] has brought a new concept of "wind-and-flip" method to construct a persistent mode magnet. No joining is needed in "wind-and-flip" method because a sliced coated conductor consisting of a closed loop of current path is used for the fabrication of pancake coil. However they have not demonstrated a persistent-mode magnet based on their concept of a "wind-and-flip" method yet.

In this study, we demonstrate a persistent mode pancake coil magnet fabricated by a "wind-and-flip" method. The fabrication of solenoid-type persistent mode HTS magnet is introduced by a slight modification of the winding method. The construction of multiple sets of pancake coil is introduced possible if a wide coated conductor is sliced into multiple slices and is wound into multiple sets of pancake coil at the same time.

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2. EXPERIMENTAL PROCEDURES

Fig. 1 shows a schematic diagram of a "wind-and-flip" method for the construction of a persistent mode HTS magnet using a coated conductor. A coated conductor with the length of 1.2 meters, which was received from SuperPower Inc. was slit along the tape length using a high speed rotating wheel. The surface of YBCO coated conductor was protected with plated copper layer. Coated conductor was fixed using a fixture in order to make sure to slit the center of the tape along the tape length. Special care was paid in order to avoid the degradation of superconductivity of the coated conductor and methanol was used as a coolant during cutting. 50 mm sections of both ends of the conductor piece have not been cut as to form a closed loop. Sliced coated conductor was carefully cleaned and dried to remove remained methanol and coated using epoxy in order to protect the superconducting layer from being exposed directly to moisture and liquid nitrogen during winding and testing of a pancake coil. The Sliced coated conductor was wound on to the disk shape Bakelite bobbin with a 40 mm diameter and insulating kapton tape was inserted between every turn. The Hall sensor was attached to the outer surface of pancake coil in order to measure the magnetic field generated from a pancake coil. Fig. 2 shows the pancake coils fabricated using a divided coated conductor. Current was supplied using a dc power supply. Test was performed by immersing the coil within liquid nitrogen bath.

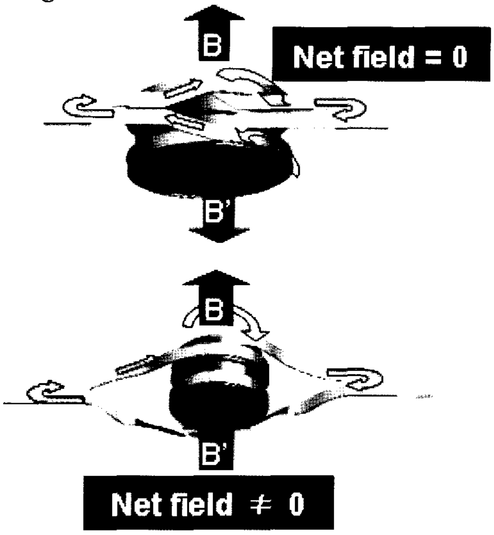

Fig. 1. Schematic diagram of "wind-and-flip" technique.

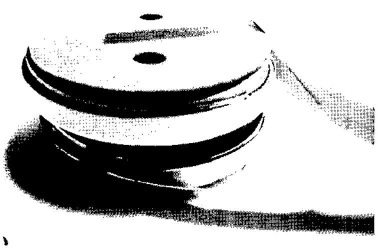

Fig. 2. Pancake coil fabricated by a "wind-and-flip" technique.

3. RESULTS AND DISCUSSION

3.1. Fabrication of a persistent mode pancake coil

Fig. 3 shows the procedure of fabricating pancake coils by a "wind-and-flip" method. Fig. 3(a) shows a divided coated conductor along the center of coated conductor. Fig. 3(b) shows a set of pancake coils wound on two bobbins with a diameter of 40 mm. The insulation sheet was inserted between conductor layers. Fig. 3(c) shows a set of pancake coils ready for a test after connecting current leads and attaching a Hall sensor and the leads for voltage drop measurement. The number of turns of each pancake coil was 8 turns and the total turns was 16 turns.

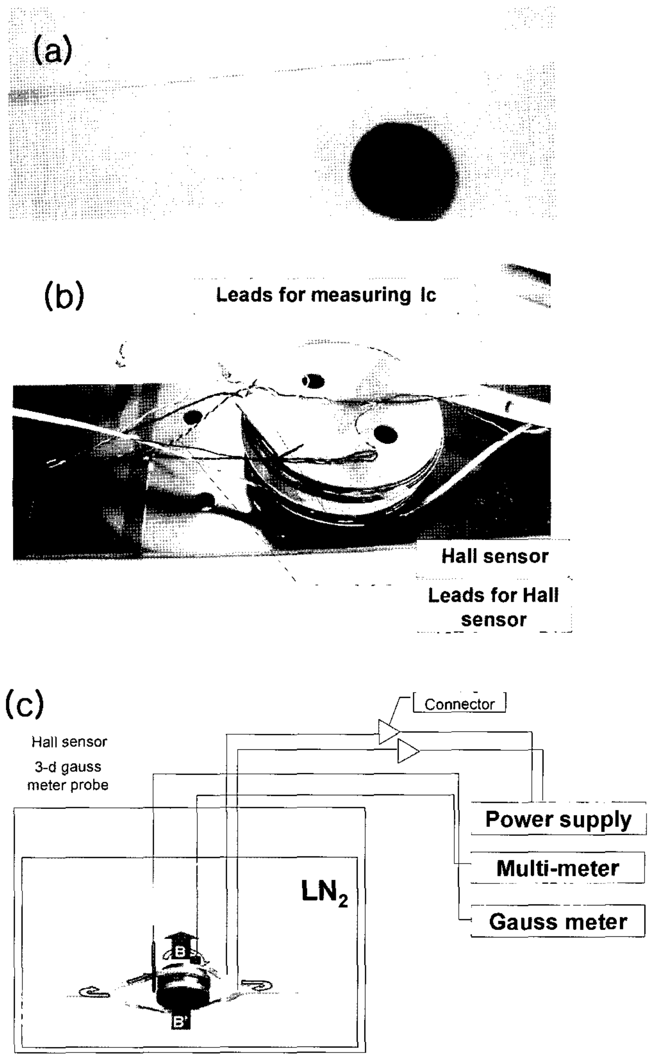

Fig. 3. Procedures for preparing pancake coils and the test setup of a persistent mode pancake coil.
(a) sliced coated conductor and bobbin (b) pancake coils with leads for measurement (c) setup for coil test.

3.2. Test results of a persistent mode magnet

The pancake coil was immersed into liquid nitrogen and waited enough time in order to cool down whole the test coil to the boiling point of liquid nitrogen. One end of conductor where current leads were connected remained outside of liquid nitrogen and kept warm for supplying the current to energize the coil. The cooled magnet was activated by flowing current of 20 A through current leads connected to the warm end of the conductor using a dc power supply. The warm end of the conductor was immersed into the liquid nitrogen after energizing the coil and then the power supply was turned off and magnetic field was monitored. 48.8 Gauss of magnetic field was measured from the coil via a Hall sensor when 20 A of current was conducted in coated conductor. There was a small difference of the magnetic field between the calculated value of 52.3 Gauss and the measured value of 48.8. This difference may be attributed to the mismatch of Hall sensor position used for calculation and real measurement. Induced current in coated conductor will be attenuated fast if there is any resistive component along a closed loop of the coated conductor. After power supply was turned off, 48.8 Gauss of magnetic field was detected from the specimen, and there was no change of magnetic field before and after power-off of power supply. The variation of magnetic field was monitored for three days and showed no changes for 72 hrs. It means that current is still flowing in the pancake coil without any attenuation of current flowing along the conductor. Therefore it can be said that there is no resistive component along the current path of the coated conductor. The above test result infers that it is possible to construct a persistent mode superconducting magnet by slitting a coated conductor.

Twisting of coated conductor cannot be avoided in the above "wind-and-flip" method. Mechanical strain can degrade the current carrying capacity of the coated conductor. However, Selvamanickam et al [6] reported that the reduction of critical current of coated conductor is negligible even though 1mm-width and 50 cm-long IBAD/MOCVD coated conductor was twisted 6 turns. Therefore, the twisting of the coated conductor applied during coil fabrication may be critical in wind-and-flip method. Also recent research by G.A. Levin et al [7] demonstrated the possibility of integrating coated conductor into magnets using sliced coated conductor for making double pancake coils, though they did not attempt to make a persistent mode magnet, their winding technique showed that the twisting of coated conductor is not a serious obstacle for making pancake coils using coated conductors. The degradation of conductor during the slitting of conductor and winding of coil could not be measured because there was no detailed information on the Ic distribution across the conductor width of the starting coated conductor received from SuperPower Inc.

3.3. Fabrication of a persistent-mode solenoid coil

In previous section, a successful operation of a persistent mode pancake coil was demonstrated. In order to construct a high field magnet, multiple sets of pancake coils are needed. Multiple power supplies are required in order to activate the multiple sets of pancake coils and the use of multiple power supply may lead to the instability of the magnetic field of the persistent mode magnet and make the system complicated. Therefore, it may be more convenient and reasonable if a solenoid coil is able to be constructed using a "wind-and-flip" technique. There may not be many issues in fabricating a solenoid-type magnet using a coated conductor if a long-length coated conductor is available. Long-length coated conductor has been already demonstrated by two companies [6-8]. It was also demonstrated using a Ag/BSSCO HTS wire having a similar dimension with coated conductor. For the construction of a solenoid coil using a sliced coated conductor, a tall bobbin was used instead of a short bobbin which was used for the winding of a pancake coil. Two solenoid coils could be wound on the bobbins and flipped. The procedure for the construction of a solenoid coil may not differ from the procedure shown in Fig. 3 except using a pair of tall bobbins.

3.4. Slitting of a wide tape and the construction of multi-set pancake coils by a wind-and-flip method

In the previous section, we suggested the construction of a solenoid coil using a long-length coated conductor by a "wind-and-flip" method for high field magnet. In order to make a high field magnet, we need an extremely long-length coated conductor. However, it may not be easy to fabricate multi-kilometer long coated conductor for the construction of an extremely high field magnet. The construction of a high field magnet may be possible if we use a broad coated conductor instead of a very long coated conductor. Currently, a 40 mm-wide coated conductor was successfully manufactured and supplied by slitting into 4 mm-width tape. Figure 4 shows the schematic drawing how to slit a wide coated conductor into multiple sections for multiple pancake coils. It is seen that a closed circuit is formed along the divided coated conductor. As shown in the previous section, two parallel divided tapes can be built into two pancake coils. Multiple sets of pancake coils can be constructed if we divide the conductor into even numbers of sliced section along the tape length. Therefore, six pancake coils can be built up using the divided tape shown in Fig. 4.

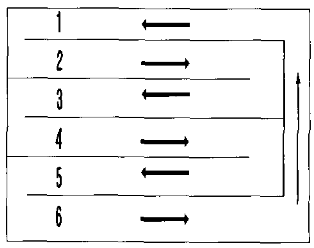

Fig. 4. Schematic drawing of slitting of a wide coated conductor for the construction of a persistent mode magnet.

The magnetic field from the coils constructed from sections #1, #3 and #5 is generated in one direction and coils constructed from sections #2, #4 and #6 will produce magnetic fields in the opposite direction. Therefore, the magnetic field produced from the set of coils constructed from sections (#1 ~ #6) will be canceled and the total magnetic field is zero. After winding 6 pancake coils, every other coil (for instance, coils constructed from sections #1, #3 and #5) is flipped and then the directions of the magnetic field will be reversed in these flipped coils. Therefore, the magnetic field generated from all the coils will be aligned in the same direction. The operation of multiple coils in persistent mode is the same as for the case of a single set of pancake coils. The number of pancake coils is only dependent on the width of the starting coated conductor and the width of the tape after slitting and therefore there is no control on the dimension of the magnet to be built and the intensity of magnetic field of the magnet.

SUMMARY

Persistent mode HTS pancake coil has been fabricated using a coated conductor by a "wind-and-flip" method using a meter-long coated conductor which was divided along the center line of the tape. The sliced coated conductor was wound on a pair of bobbin with a diameter of around 5 cm. By flipping one of the coils, a persistent mode magnet was constructed. Permanent current was induced by allowing current to flow into the coil immersed in liquid nitrogen pool. Magnetic field of 48.8 Gauss was detected when 20 A of current was flowing in the pancake coils. It was observed that there is no variation of magnetic field for 72 hr after switching off of the power supply.

It is introduced that a pair of solenoid coil also could be prepared by a "wind-and-flip" method using a long-length coated conductor. The technique how to construct multiple sets of pancake coils by the "wind-and-flip" method is shown using a wide coated conductor in order to construct a high field magnet operating in a persistent mode.

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