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著者	伊藤　悟
journal or publication title	IEEE Transactions on Applied Superconductivity
volume	19
number	3
page range	1536-1539
year	2009
URL	http://hdl.handle.net/10097/46519

doi: 10.1109/TASC.2009.2019057

Mechanical Butt Joint of Laminated HTS Cable With Metal Jacket for Remountable HTS Magnet

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***Abstract*—The remountable HTS magnet was proposed to allow a superconducting magnet for a fusion reactor to be assembled and to allow a failed part of the magnet to be replaced or repaired. In this study, joint resistance was evaluated in a mechanical butt joint of a stacked BSCCO 2223 cable with a copper jacket. The fabricated cables could reduce joint resistance to be 400–500 $\mathrm{n}\Omega$ with a silver-plated layer or an indium-film applied to the joint surface. The experimental results also showed that parallel joint force is required to reduce joint resistance more without deformation of the joint surface configuration.**

***Index Terms*—Fusion reactors, high-temperature superconductors, power cable connecting, superconducting magnets.**

I. Introduction

THE remountable high-temperature superconducting (HTS) magnet was proposed to allow a superconducting magnet for a fusion reactor to be assembled and to allow a failed part of the magnet to be replaced or repaired [1], [2]. Fig. 1 shows a schematic view of the remountable magnet applied to the helical coils of LHD. In this design, the magnet is separated into some parts and they are mounted and demounted iteratively. This concept has a possibility to contribute greatly to helical reactors and spherical tokamaks, which have complex magnet configurations. Although this concept was also proposed for low-temperature (LTS) superconducting magnet [3] and demountable joint of a LTS conductor was achieved in ITER CS coil for example [4], a HTS is more stable in such a demountable joint due to its high heat capacity. A HTS magnet could be used in a future fusion reactor and the remountable HTS magnet can be applied at that time.

Mechanical butt joint of a BSCCO 2223 cable, where cross-sections of the cable are just jointed mechanically, has been investigated for the concept [5]–[7]. Since a first target is a feasibility demonstration of the design by proving robustness against heat generation at the joint parts, a BSCCO 2223 tape has been used as a test material although it is not available under a large magnetic field in a fusion reactor due to degradation of its performance. In those previous studies, the cable was made by stacking 10 sheets of BSCCO 2223 tape and bundling them with low temperature solder as shown in Fig. 2(a). In addition, the joint surface of the cable was inclined at a 45-degree angle with respect to the cable length direction. Mechanical joint force was given to the joint region in a perpendicular direction to the cable. The results showed that electric resistance at the joint region (joint resistance) decreased when compressive stress acting to the joint region (joint stress) increased up to a certain value, then the joint resistance started to rise with an increase in the joint stress. There existed several problems for the mechanical butt joint of the stacked cable; Joint force induced excessive strain to the cable causing degradation of critical current; Buckling and deformation of the joint surface are induced by slippage between layers of the stacked BSCCO 2223 cable; Metal-plating was difficult to be applied to the joint surface due to the layer peeling and the deformation of the joint surface.

In this study, a laminated BSCCO 2223 cable (a stacked BSCCO 2223 cable) with a metal jacket shown in Fig. 2(b) is used as a test cable to strengthen the cable structure and to prevent the joint surface from being deformed. A relationship between joint resistance and joint stress is evaluated where the cable is cooled by liquid nitrogen. The evaluation is performed for several samples whose joint surface is coated with silver or indium layers. These results are reported in this paper.

II. Experimental Set-Up

A. Test Samples for Joint Tests

Test cables used in this study are shown in Fig. 2; A conventional stacked BSCCO 2223 cable named Test Cable A; A stacked BSCCO 2223 cable with a copper jacket named Test Cable B. In this study, the Test Cable B is used mainly since the purpose of this study is investigating joint performance with the stacked cable with a metal jacket. The Test Cable B is made by laminating 10 sheets of BSCCO 2223 tape inside the jacket and they are fixed with Ag-Sn solder. Copper is chosen as a material of the jacket because its thermal conductivity is large and its thermal strain from room-temperature to liquid nitrogen temperature is close to the BSCCO 2223 tape's one. Critical currents of the Test Cable A and the Test Cable B are respectively about 470 A and about 740 A at liquid nitrogen temperature and self-magnetic field. Both cables are cut down with an inclination angle of 45 degrees to make the joint surface. Then the surface is polished with alumina particles whose diameter is about 3 $\mu\mathrm{m}$.

Since joint resistance strongly depends on the number of contact points on the joint surface, some treatments on the joint surface are performed to increase the number of contact point for the Test Cable B; The joint surface is electro-plated with a silver layer whose thickness is 5 $\mu\mathrm{m}$, 15 $\mu\mathrm{m}$ or 25 $\mu\mathrm{m}$; A silver-film of 10 $\mu\mathrm{m}$, 30 $\mu\mathrm{m}$ or 50 $\mu\mathrm{m}$ is inserted between the joint surfaces; An indium-film of 50 $\mu\mathrm{m}$ is inserted between the joint surfaces. The above treatments are applied only to the BSCCO 2223 tape

Manuscript received August 18, 2008. First published June 05, 2009; current version published July 15, 2009. This work was supported in part by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (B), 18360440, 2007.

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Digital Object Identifier 10.1109/TASC.2009.2019057

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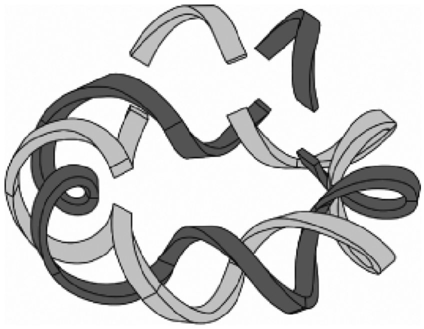

Fig. 1. Schematic view of remountable HTS magnet.

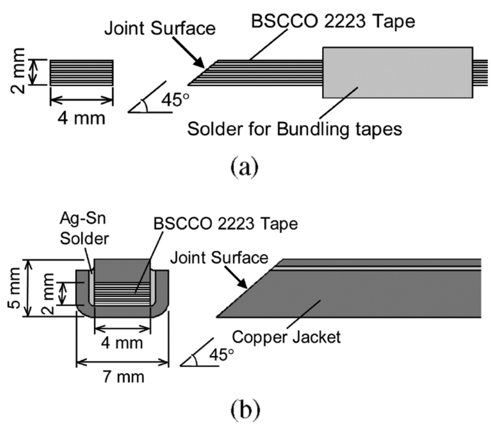

Fig. 2. Test cable. (a) Conventional stacked BSCCO 2223 cable (Test cable A) and (b) stacked BSCCO 2223 cable with copper jacket (Test cable B).

TABLE I
TEST SAMPLES

Sample Name		Test Cable	Joint Surface Condition	Thickness of Metal Layer
A(Dry)		A	Only polished	
B(AgP)	B(AgP-5)	B	Electro-Plated with a Silver Layer	5 μm
	B(AgP-15)			15 μm
	B(AgP-25)			25 μm
B(AgF)	B(AgF-10)	B	Inserting a Silver-Film	10 μm
	B (AgF-30)			30 μm
	B (AgF-50)			50 μm
B(InF)	B(InF-50)	B	Inserting an Indium-Film	50 μm

region on the joint surface, are not applied to the metal jacket region because gap is generated at the BSCCO 2223 tape region due to a slight difference between thermal strains of the jacket and the tape. The above samples for the butt joint are described in Table I. The sample names shown in Table I are used to explain experimental results.

B. Experimental Set-Up

Fig. 3 shows the test section for the experiment of the mechanical butt joint. A pair of the test cables is fixed on the test section base to be jointed mechanically. Joint stress is imposed by the rod above the center of the test cable. Sizes of the rod surface contacting onto the cable are 4.5 mm × 4.5 mm for the Test Cable A and 6 mm × 4.5 mm for the Test Cable B. The position of the rod is controlled through rotating the handle above the rod. The joint stress is measured through the load cell located between the handle and the rod. Voltage drop between the voltage taps, whose distance is 60 mm, is measured to estimate joint resistance. The test section is cooled by liquid nitrogen.

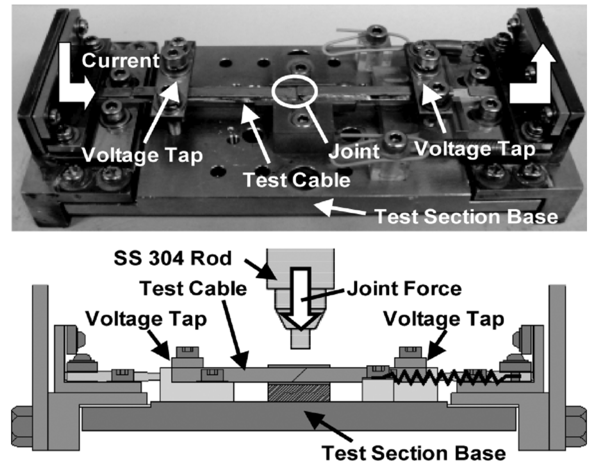

Fig. 3. Experimental set-up.

III. RESULT AND DISCUSSION

A. Compressive Stress Dependence of Critical Current

Before carrying out the joint test, compressive stress dependences of critical current of the test cables are evaluated. The test cables are not cut down in this experiment, which means the cables have no joint region. Fig. 4 shows a relationship between compressive stress given by the rod and critical currents of the Test Cable A and the Test Cable B. The vertical axis of Fig. 4 indicates ratio of critical current at each stress value to that at zero stress. The result shows that the Test Cable B keeps its critical current at larger compressive stress compared to the Test Cable A. This is caused by stress concentration occurring at the edge of the rod giving the compressive stress. In the case of the Test Cable A, the stress concentration occurs on the BSCCO 2223 tape region and it damages the BSCCO 2223 tape. On the other hand, the stress concentration occurs on the copper jacket in the case of the Test Cable B, which can prevent the BSCCO 2223 tape region from being deformed. The fact implies that the cable with a metal jacket has a possibility to achieve lower joint resistance because the resistance can decrease with an increase in the joint stress without degradation of critical current up to larger stress value.

B. Joint Tests

Joint resistance is evaluated for each sample shown in Table I. At first, results for the Test cable B are discussed in this subsection. Fig. 5 shows a relationship between joint stress and joint resistance at 300 A in the case of B(AgP). The joint resistances decrease with an increase in joint stress in all cases. Joint resistance in B(Ag-5) and that in B(Ag-15) are almost the same, but that in B(Ag-25) is larger than the two resistances. The difference of joint resistance in B(Ag-25) from that in B(Ag-15) or in B(Ag-5) is about 0.5 $\mu\Omega$ to 10 $\mu\Omega$. On the other hand, a

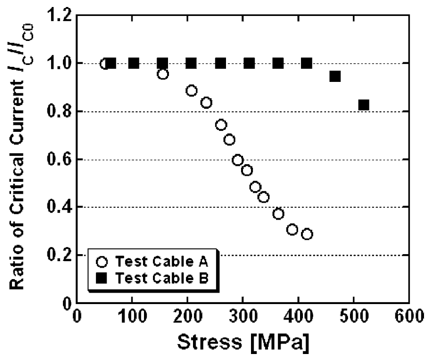

Fig. 4. Compressive stress dependence of critical current.

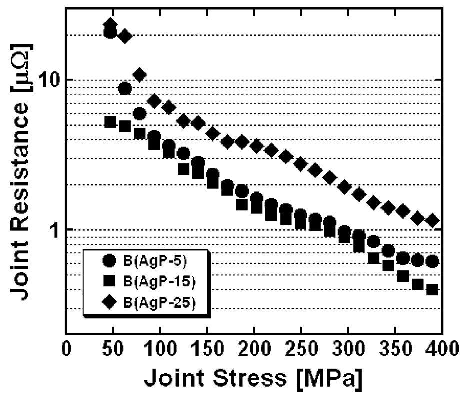

Fig. 5. Relationship between joint stress and joint resistance in the case of B(AgP).

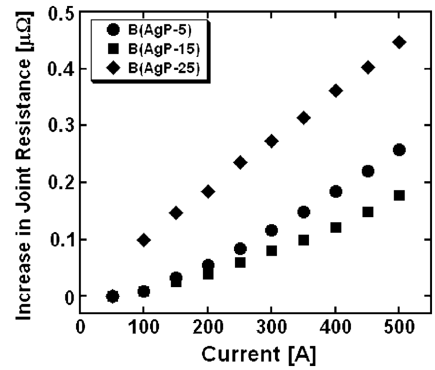

Fig. 6. Relationship between applied current and increase in joint resistance starting from the resistance at 50 A in the case of B(AgP).

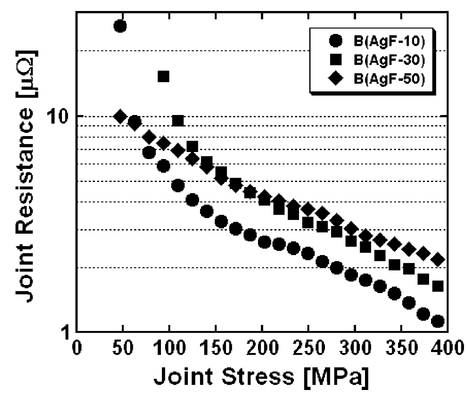

Fig. 7. Relationship between joint stress and joint resistance in the case of B(AgF).

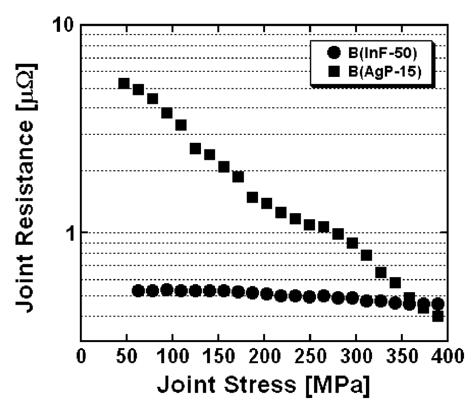

Fig. 8. Relationship between joint stress and joint resistance in the cases of B(AgP-15) and B(InF-50).

difference of electric resistance of the silver layers between respective cases is about 5 nΩ to 10 nΩ. The fact indicates that the difference of the joint resistance is not caused by the difference of the resistance of the silver layers. Fig. 6 shows a relationship between applied current and an increase in the joint resistance, starting from the resistance at 50 A in B(AgP) when the joint stress is 400 MPa. The joint resistances increase when the applied current also increases. The rise in the joint resistance is caused by transport current flowing the silver stabilizer region near the joint surface, which was also shown in a previous study [5]. This result shows that the superconducting filaments near the joint surface in B(AgP-25) is more degraded than that in B(AgP-5) and B(AgP-15). The degradation can be caused by treatment time for the electro-plating, which also affects the result shown in Fig. 5.

Fig. 7 shows a relationship between joint stress and joint resistance in B(AgF) when applied current is 300 A. In this case, joint resistance is smaller when thickness of the silver-film becomes smaller. This is caused by hardness of the silver-film because resistance of the silver film itself is much smaller than the joint resistance. In addition, the value of joint resistance in B(AgF) is larger than that in B(AgP) as shown in Figs. 5 and 7. The number of mechanical interface could influence the result; There exists one interface in B(AgP) whereas two interfaces exist in B(AgF).

Fig. 8 shows a relationship between joint stress and joint resistance in B(InF-50) when applied current is 300 A. Additional to this, the result in B(AgP-15) is shown in this figure. Fig. 8 shows that the joint resistance in B(InF-50) is relatively low even though joint stress is small. An indium-film is so soft that the number of the contact points can be larger with low joint force. Remounting the cable without degradation of the cable could be achieved with an indium-film. Since resistance of silver is smaller than that of indium, a cable with a silver-plated layer can reduce joint resistance more when the joint stress becomes larger.

Fig. 9 shows relationships between joint stress and joint resistance in the cases of A(Dry) and B(AgP-15). Joint resistance in B(AgP-15) does not rise even though the joint stress becomes 400 MPa whereas joint resistance starts to increase from 250

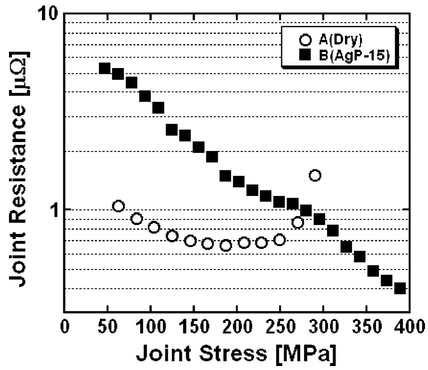

Fig. 9. Relationship between joint stress and joint resistance in the cases of A(Dry) and B(AgP-15).

MPa in A(Dry). The compressive stress dependences of critical current of the two cables shown in Fig. 4 could influence this result. On the other hand, the joint resistance in A(Dry) is much smaller than that in B(AgP-15) when the joint stress is small. This fact implies that deformation of the cable increases the number of contact point on the joint surface in this mechanical butt joint system, where joint surface is inclined at a 45-degree angle with respect to the cable length direction and the joint force is given from a perpendicular direction to the cable. For this configuration, joint force should be applied in parallel to the cable length direction because the test cable can increase the number of contact point without deformation of the joint surface configuration, just with deformation of a metal layer applied on the joint surface, silver or indium, for example.

In this experiment, joint resistance of 400 $\mathrm{n}\Omega$ is obtained in B(AgP-15) and 450 $\mathrm{n}\Omega$ is obtained in B(InF-50) at 300 A. A HTS cable transporting several tens of kilo ampere has larger cross-section and the joint resistance could be reduced 10^{-1} or 10^{-2} times for the cable. However current distribution would be changed with magnetic field, which could affect the joint performance. In addition, an increase of the current rises the joint resistance as shown in Fig. 6. Therefore it is required to evaluate the joint resistance at larger current and magnetic field as a future task. For the concept of remountable HTS magnet, the joint surface is required not to be deformed macroscopically and not to be detached with various electromagnetic forces and thermal strain. For the issues, performing structural analysis and introducing mechanism giving parallel force to the joint region also must be considered as future tasks. In addition, the mechanical joint method should be applied to a YBCO cable or something, which can keep high critical current under fusion reactor environment.

IV. CONCLUSIONS

In this study, joint resistance in mechanical butt joint of a stacked BSCCO 2223 cable with a copper jacket was evaluated and the result was compared to that of a normal stacked BSCCO 2223 cable. The results obtained by this study are summarized as follows;

1) The stacked BSCCO 2223 cable with a copper jacket could keep its critical current with larger compressive stress up to 400 MPa whereas critical current of the normal stacked BSCCO 2223 cable started to decrease at 150 MPa. This fact shows the cable has a possibility to achieve lower joint resistance because the resistance can decrease with an increase in the joint stress without degradation of critical current up to larger stress value.
2) Even though difference of thermal expansions between the BSCCO 2223 tape and the jacket material is slight, narrow gap is generated at the joint region. Some treatment to fill a metal layer in the gap are required in the mechanical butt joint system.
3) Joint resistance was reduced to be 400 $\mathrm{n}\Omega$ with a silver-plated layer of 15 $\mu\mathrm{m}$ at 300 A. In the silver-plated layer case, longer treatment time for the electro-plating could cause an increase in joint resistance.
4) Applying silver-plating to the joint surface was more effective to reduce joint resistance than inserting a silver-film between the joint surfaces. This is because there exists one mechanical interface for the silver-plating case whereas two mechanical interfaces exist for the silver-film case.
5) Joint resistance became relatively low even though joint stress is small when an indium-film was inserted between joint surfaces. The minimum resistance at 300 A in this case was 450 $\mathrm{n}\Omega$. Remounting the cable without degradation of the cable could be achieved with an indium-film.
6) Deformation of the joint region reduces joint resistance in this mechanical butt joint system although the deformation induces a decrease in critical current. Parallel joint force is ideal to increase the number of contact point without deformation of the joint surface configuration, just with deformation of a metal layer applied on the joint surface.
7) Evaluating the joint resistance at larger current and magnetic field, performing structural analysis and introducing mechanism giving parallel force to the joint region are considered as future tasks. In addition, the mechanical joint method should be applied to a YBCO cable or something, which can keep high critical current under a fusion reactor environment.

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