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INVESTIGATION OF TWISTED STACKED-TAPE CABLE CONDUCTOR

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ABSTRACT

A cable fabrication method of a twisted stacked tape conductor for HTS YBCO tapes has been developed and tested. A 2 m long, 32-tape conductor of 4 mm width YBCO was fabricated with a 200 mm twist pitch. The measured critical current of the straight cable agreed with the expected values estimated from the self-magnetic field. The 2 m long cable wound on a surface of 0.5 m diameter circle did not show any degradations. It has been confirmed through tests with single tape and cable tests that it is possible to develop a YBCO multiple-tape stacked cable with a 200 mm twist pitch and to make a coil with an innermost turn of at least 0.5 m diameter. A joint method for a multi-tape YBCO cable using BSCCO tapes has been developed and operated at 2.2 kA. AC losses of a twisted stacked YBCO tape cable also have been analyzed. The twisted stacked-tape cabling method for YBCO tapes will be very useful for high-current, high-field magnets for various applications.

KEYWORDS: Cabling, critical current, AC loss, HTS, termination, joint.

INTRODUCTION

We have been developing a High Temperature Superconductor (HTS) tape cabling method having a "twisted stacked-tape" geometry to provide a simple, high current density and scalable cabling method [1, 2] applicable to a large scale magnet. This technique will be attractive for various large magnets such as fusion, SMES, compact superconducting cyclotron, as well as electric power transmission cables. HTS, especially YBCO coated tapes, have excellent high current capabilities at high magnetic fields. HTS cables carrying currents up to about 3 kA have already been fabricated by either helically winding the tapes in one or more layers annularly on a cylindrical mandrel [3-5], or by a specially cut, stacked and transposed multi-tape conductor of ROEBEL Assembled Coated Conductor

(RACC) [6, 7]. However, these cabling concepts are not suitable to manufacturing processes for high current, high current density conductors and Cable-in-Conduit Conductors (CICC). In this paper we present experimental and analytical results for sub-scale twisted stacked-tape cables made of 2G YBCO tapes, including AC loss analysis, a cable termination method, cable bending tests, and a 2 m 32-YBCO-tape cable test.

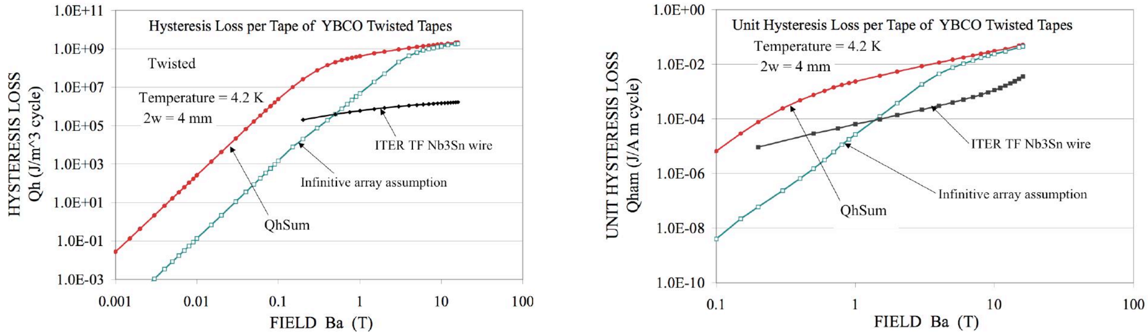
AC LOSSES

Existing formulations of the hysteresis losses without a transport current for both parallel and perpendicular magnetic fields acting upon a single flat superconducting tape and a stacked-tape cable of an infinite number of tapes were used to evaluate the hysteresis losses for twisted stacked-tape cables. The main benefit of a twisted stacked-tape cable with regard to AC losses is to reduce induced loop currents and coupling losses by twisting. The details are presented in [8]. The main calculated results of AC losses for a twisted stacked-tape conductor are summarized below.

Hysteresis loss of twisted stacked-tape conductor

Hysteresis losses of a twisted stacked-tape cable made of HTS tapes were estimated based on existing theories of a slab model in a parallel field [9], a thin tape in a perpendicular field [10, 11] and an infinitively stacked tape array in a perpendicular field [12]. In order to simulate twist in the cable, the field is rotated 360 degrees on a straight conductor over one twist pitch length. The effective fields on the hysteresis loss calculation are composed of parallel and perpendicular field components of the external field. An averaged value of the hysteresis loss per tape of a twisted conductor, Q_{hSum}, was calculated with an integration of the sum of the two components due to parallel and perpendicular fields over one twist pitch [8].

Hysteresis losses have been evaluated taking into account the critical currents for magnetic fields between 1 mT and 16 T using SuperPower critical current data at 4.2 K [13]. Hysteresis losses for a twisted YBCO single tape due to the perpendicular field component of the applied field dominate the total loss since the hysteresis loss due to the parallel field component is much smaller than that due to the perpendicular field [8]. The hysteresis loss of a twisted tape over one twist pitch in high fields is about 2/π times (64%) the hysteresis loss of a single tape in perpendicular field. That is, hysteresis loss of a twisted tape at high fields (≥1 T) is reduced to 64% from that of purely perpendicular fields by twisting [8]. Hysteresis losses Q_{hSum} of twisted YBCO tapes with a 4 mm width are shown in FIGURE 1(a).



(a) (b)

FIGURE 1 Calculated hysteresis losses O_{hSum} for a twisted YBCO tape of the width *2w*=4 mm, and hysteresis loss per tape of an infinite tape array tightly stacked (*D*=0.1 mm) obtained from the perpendicular field component by averaging over one twist pitch simulating twisting. Evaluated hysteresis loss of an ITER TF wire is also plotted. (a) Hysteresis losses per unit volume per cycle. (b) Hysteresis losses per ampere and per meter (J/A·m cycle).

When YBCO tapes are stacked in the parallel field (parallel to the tape face), hysteresis losses can be calculated in the same way as that for a single tape. However, in the perpendicular field to the stacked tape the magnetic field shielding effect must be take into account [12]. Hysteresis losses for an infinitively stacked tape array exposed to perpendicular field have been obtained by Mawatari [12]. The calculated hysteresis loss (per unit volume of superconductor per cycle) for an infinitively stacked YBCO tape (4 mm width) is shown in FIGURE 1(a) [8]. The calculated losses for $B_a=\pm 12$ T full cycle are $1.6\text{x}10^9$ J/m^3 (6.2 J/m), obtained by the twisted infinite array model. By comparison, the estimated hysteresis loss of an ITER TF Nb_3Sn wire is plotted in FIGURE 1(a), based on the ITER specifications; diameter 0.82 mm, twist pitch 15 mm, `critical current I_c=264 A at 12 T and 4.2 K, hysteresis loss about $1\text{x}10^6$ J/m^3 for ± 3 T full cycle, and the critical current field dependence evaluated for a typical ITER TF wire. The estimated hysteresis loss of a Nb_3Sn wire of ITER TF magnets is about $1.6\text{x}10^6$ J/m^3 (0.4 J/m cycle) for ± 12 T full cycle.

The hysteresis losses per unit critical-current are the relevant parameter, instead of the hysteresis losses per unit volume, since the current density of YBCO tape is much higher than that of Nb_3Sn wire. The hysteresis losses plotted in FIGURE 1(a) are converted to hysteresis losses per unit current and unit length (J/A·m cycle), and they are plotted in FIGURE 1(b). Comparing 4 mm width YBCO tape (Ic=207 A) with 0.82 mm diameter Nb_3Sn wire (Ic=264 A) at 12 T and 4.2 K, hysteresis loss per unit current and unit length of a stacked YBCO conductor is about one order of magnitude larger than that of the ITER TF wire at 4.2 K, although the volume hysteresis loss of the YBCO tape is three orders of magnitude larger than that of the Nb_3Sn wire. Even if hysteresis loss of HTS YBCO tape is one order of magnitude larger than that of Nb_3Sn wire at 4.2 K, the AC losses of HTS tapes are less critical, since the HTS tapes can be operated at higher temperatures (20 K - 50 K) than that of Nb_3Sn wires and thermal capacities of composite materials are much higher at those temperatures compared to values at 4.2 K.

Coupling losses of twisted stacked-tape conductor

A current induced between stacked tapes by a parallel field to the tape creates a coupling loss. The induced current is proportional to the square of the twist pitch length of a twisted stacked-tape cable. The time constant of the coupling current is also proportional to the square of the twist pitch length [9]. The coupling current loss is proportional to the time constant. Therefore it is desired to reduce the twist pitch. However, this is limited by strain and other mechanical properties of HTS tapes due to twisting. The coupling loss is known to decrease by increasing the transverse resistance between tapes. However, in order to allow current sharing between tapes lower transverse resistance is desired. It is important to optimize electrical resistances between tapes by using proper electric filler such as soldering. It is also important to maintain a proper support for the twisted cable under the electromagnetic force during operation involving high current and high field.

It is noted that the twisted stacked-tape cabling is beneficial to operational stability by reducing magnetic diffusion time constant, as that of conventional superconducting wires treated with twisting technologies. The twisted stacked-tape conductors will be useful to high current conductors for DC or low-frequency high field magnets and DC power transmission cables.

YBCO CABLE TERMINATION METHOD

For a multi-tape stacked conductor of YBCO tapes, the conductor terminations and joints between the tapes must be fabricated properly taking into account the asymmetric electric conductivity (The silver side of the tape has better electric transverse conductivity than the substrate side with additional buffer layers.). A termination method for a YBCO tape cable has been developed that uses symmetric HTS tapes such as BSCCO tapes as shown in FIGURE 2(a) [14]. This figure illustrates a stacked YBCO tape cable (right side) composed of multiple tape cables to be terminated to a copper lead (left). The conductive side (silver layer side) of each tape of the stacked YBCO tapes is connected to a BSCCO tape. The opposite end of the BSCCO tapes is soldered to a copper lead. Additional BSCCO tapes, if required, are inserted between the BSCCO tapes to obtain a uniform height and match the height required to insert the YBCO tapes between BSCCO tapes at the joint section. In the YBCO/BSCCO joint section, YBCO tapes (conductive silver side) are soldered to BSCCO tape to make low resistive connection for a permanent joint, or they are jointed with mechanical pressure contacts without soldering for a demountable joint.

FIGURE 2(b) shows a YBCO cable termination used for a stacked tape cable made from 43 YBCO tapes. The termination consisted of 44 BSCCO tapes (4 mm width, 220 mm length) with a 19.1 mm diameter copper tube of 100 mm length. 100 mm of the BSCCO tapes were soldered together inside the copper tube. The copper tube was clamped to a copper block, shown in FIGURE 2(c), without soldering to connect to a copper power cable. The stacked YBCO tapes were sandwiched between the BSCCO tapes, and then the solder-free stacked tape assembly was clamped with 70 mm length G10 plate and bolted.

Solder-free joint resistances between YBCO and BSCCO tapes were measured for ten YBCO tapes among 43 tapes one at a time with a current of up to 50 A in liquid nitrogen. The results are shown in FIGURE 3. The contact joint resistances decreased with the contact pressures, which were determined by the applied torques to the cramp bolts. At a contact pressure of 55 MPa the measured resistances were about 1 μΩ. The standard deviations of the measured resistances obtained for ten samples were also decreased with the applied pressure. The resistance between the copper tube and the copper block was about 0.5 μΩ including copper resistances. The 44 BSCCO tape terminators have been operated up to 2.2 kA.

(a) (b) (c)

FIGURE 2 Copper-BSCCO-YBCO termination. (a) Schematic illustration of YBCO tape sandwiched between BSCCO tapes. (b) Fabricated 44-BSCCO-tape terminator (left) for a 43 stacked-tape YBCO conductor (right). Stacked YBCO tapes were sandwiched between the BSCCO tapes (center) which were clamped with 70 mm length G10 plate without soldering. The BSCCO tapes were soldered in a copper tube (left). (c) The copper tube was clamped on a copper block to connect to a copper power cable.

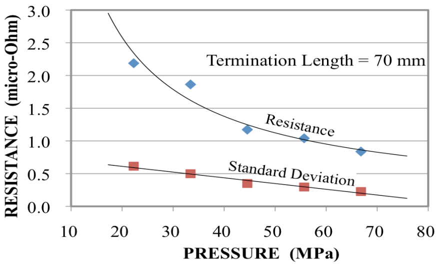
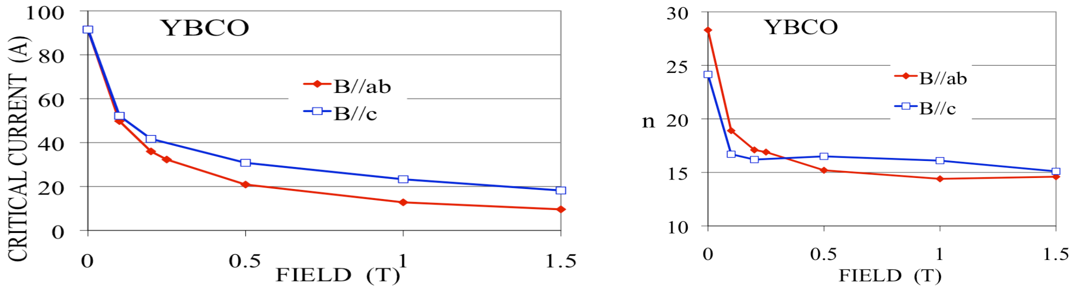


FIGURE 3 Pressure contact joint resistances between YBCO and BSCCO tapes as a function of the contact pressure, measured for 70 mm length terminator. Standard deviations of the resistances obtained for ten samples are also shown.



(a) (b)

FIGURE 4 Critical current behaviors of SuperPower Inc. YBCO Advanced Pinned tape in parallel (B//ab) and perpendicular (B//c) fields at 77 K. (a) Critical current. (b) n-values as a function of the magnetic field.

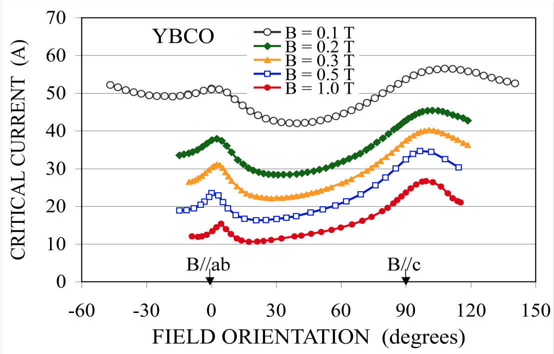


FIGURE 5 Field orientation effect of the critical currents at various magnetic fields between 0.1 T and 1.0 T at 77 K.

This method can be used for a termination of a stacked tape cable, and also for a joint between stacked tape cables. The termination and joint methods allow design flexibilities of joint fabrications either for a permanent soldered joint or a demountable joint. Furthermore by using higher T_c HTS tapes such as BSCCO tapes, degradations of YBCO conductors due to temperature rise at the joint area can be reduced.

CABLE TESTS

Evaluations of YBCO AP tape

YBCO Advanced Pinned Zr-doped tapes from SuperPower Inc. were used in the tests. FIGURE 4 shows measured critical currents of the tape in parallel (B//ab) and perpendicular (B//c) fields up to 1.5 T at 77 K. The critical current dependences upon field orientation measured at various magnetic fields between 0.1 T and 1.0 T are shown in FIGURE 5.

The critical currents in perpendicular field were larger than those in parallel field at 77 K. This characteristic has previously been observed in SuperPower Zr-doped YBCO tapes [15]. For twisted stacked-tape conductor the perpendicular self-field to the stacked tapes is substantial due to tightly packed nature of the high-density conductor. Because of the improved performance of the SuperPower tapes to fields normal to the tapes, the presence of strong perpendicular fields in the twisted stack cable will not be a negative factor any more.

Cable bending Test

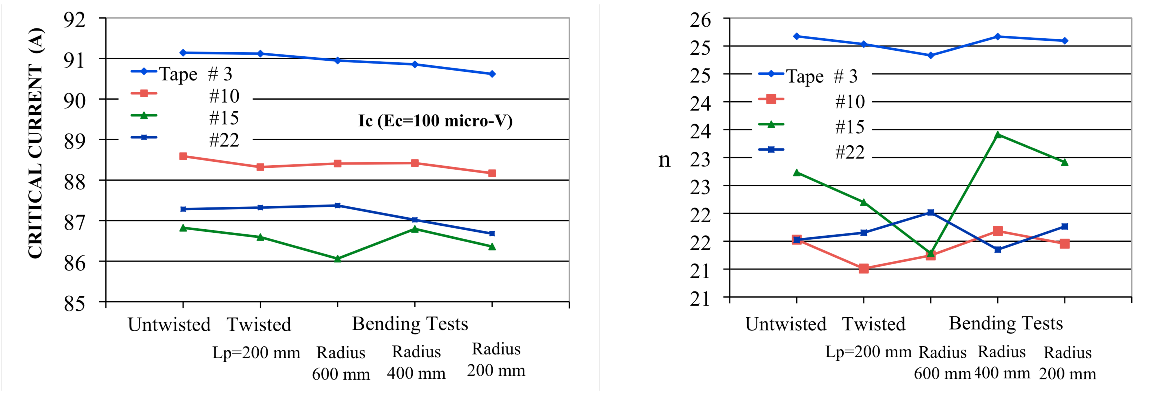
Twisting and bending tests of a short twisted stacked-tape cable were performed using a 432 mm length cable made from 4 YBCO tapes and 20 YBCO dummy tapes (low performance tapes). The 4 mm YBCO tape stacked cable were mounted between copper strips (4.8 mm wide and 0.82 mm thick) at the bottom and top. Four YBCO tapes were embedded in the tape stack at the locations #3, #10, #15 and #22 from the top. The 4 tested YBCO tapes were electrically insulated with 68 μm Kapton tape placed between the dummy tapes adjacent to the tested tapes and the YBCO tapes. The critical currents in each of the four tapes among 24 tapes were measured.

The critical current of each tested tape was measured prior to twisting the cable. The cable was then twisted with a twist pitch of 200 mm, followed by bending tests. Various bending radii were used to investigate the dependence of the critical currents under bending. The tests were carried out at 77 K, and the bending radii used were 600 mm, 400 mm and 200 mm. The results obtained for the four tapes are plotted in FIGURE 6. The results indicated no significant degradation of performance of the cable with twist pitches as short as 200 mm and bending radius as small as 200 mm. From these short cable results, we concluded that a twisted stacked-tape conductor could be fabricated with a twist pitch of 200 mm and the bending radius of 200 mm.

2 m Cable test

An 2.13 m long cable was fabricated by the similar technique used for the bending test cable described above. The length includes joint sections of about 150 mm at each end. In this long cable test, 32 YBCO tapes were stacked with two copper strips (0.82 mm thickness and 4.8 mm width). The stacked tape conductor cross-section was approximately a square shape of 4.8 mm x 4.8 mm. The cable was twisted with a twist pitch of 200 mm. A section of the 2 m length conductor is shown in FIGURE 7.

The straight cable was tested in liquid nitrogen in self-field. The critical current at the criterion E_c=100 micro-V/m was 1.53 kA with an n-value of 24.1. The critical currents of SuperPower YBCO tapes used for the cable fabrication were about 85 A at 77 K. Therefore, the critical current degradation was about 44%. FIGURE 8 shows magnetic self-field distribution calculated for 32 YBCO tapes tightly stacked, operated with the cable current of 1.53 kA [2]. The fields distribute between 0 and 150 mT over the cross-section. The averaged value of the total fields was calculated to be 100.2 mT. From FIGURE 5 the minimum critical current of a single tape is about 42 A at 100 mT. Therefore the 32-tape cable can carry at least 1.34 kA. From this analysis, the measured cable critical current of 1. 53 kA can be explained by the self-field effect of the conductor [2]. This result indicates that the YBCO tapes did not degrade by the cable fabrication method.



(a) (b)

FIGURE 6 Bending tests of the critical currents for a 432 mm length, 24 YBCO stacked tape cable. After testing the untwisted cable, the cable was twisted with a twist pitch of 200 mm. Then the twisted cable was wound around spools of radii of 600 mm, 400 mm and 200 mm sequentially, and the critical currents were measured at 77 K. (a) Critical current. (b) n-values.

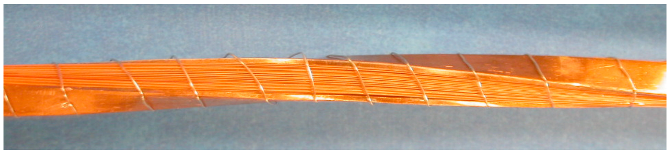


FIGURE 7 A section of 2 m length, 32 tapes, YBCO stacked-tape cable twisted with a pitch of 200 mm.

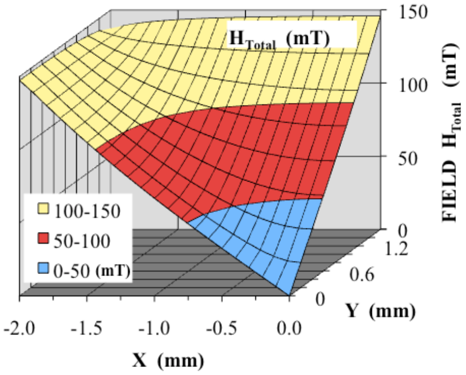


FIGURE 8 Self-field distribution over a cross section (4 mm x 3.2 mm) of a 32 YBCO stacked-tape cable carrying 1.53 kA. Amplitudes of the self-fields are plotted over one quadrant of the cable cross section.

FIGURE 9 One turn coil of 2 m long twisted stacked-tape cable mounted on a side surface of a 0.5 m diameter disk.

(a) (b)

FIGURE 10 (a) Three helical grooves in a rod 9.53 mm diameter, groove pitch 254 mm, depth 2.92 mm, width 4.32 mm. (b) Three helical channel CICC mockup composed of a 20-YBCO-tape (Total 60 YBCO tapes) cable in each groove on a copper diameter 9.53 mm rod in a 12 mm x 12 mm conduit.

In order to examine a feasibility of winding capability of the twisted stacked-tape HTS conductor, the 2 m cable was mounted along the circumference of a 0.5 m diameter spool to form one turn coil as shown in FIGURE 9, and tested in liquid nitrogen. The test result of the critical current was 1.54 kA with n=23.7 which showed no degradation due to bending of 0.5 m diameter. This result agrees with the bending tests of the short conductor described above.

CICC FABRICATION METHOD OF TWISTED STACKED-TAPE CABLE

Fabrication methods of a twisted stacked-tape CICC have been investigated. Single and three helical grooves on a copper rod were fabricated in short lengths with a four-axial CNC Milling machine. Such a copper rod with helical groove channels will be developed with extrusion. A stacked tape conductor or a twisted stacked-tape cable can be embedded in each groove to make a basic round conductor. FIGURE 10 shows a CICC mockup having three helical grooves and a total of 60 YBCO tapes [16].

CONCLUSIONS

The critical current of a 2 m long, 32-YBCO-tape twisted stacked conductor with 200 mm twist pitch was 1.53 kA at 77 K which agreed with the expected values estimated from the self-field effect. The same cable wound on a 0.5 m diameter circle resulted in the same critical current. It indicated that the YBCO tapes did not degrade by the fabrication method. It is possible to develop a HTS stacked cable with a 200 mm twist pitch and make a coil of an innermost turn of at least 0.5 m diameter. Further optimization of the minimum bending diameter will be desired. Sheathed conductors and soldering effects should be investigated.

Hysteresis loss per unit current and unit length of a stacked YBCO conductor at 4.2 K is about one order of magnitude larger than that of the ITER TF wire. However, the AC losses of HTS tapes will be less critical since the HTS tapes can be operated at higher temperatures (20 K - 50 K) with much higher thermal capacities of composite materials than that of Nb_3Sn wires.

A cable joint fabrication method using BSCCO tapes has been developed for asymmetric conductive YBCO tapes. In this method the YBCO tapes were terminated through the BSCCO tapes. The connection between the opposite ends of the BSCCO tapes were soldered to copper. The joint resistance of a solder-free contact between YBCO and BSCCO tapes was below 1 μΩ per tape joint at the contact pressure of about 55 MPa. The solder-free mechanical contact joint method is of particular interest because it can be used for demountable joints. The 44 BSCCO tape terminators without soldering have been operated at up to 2.2 kA in liquid nitrogen.

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