Scale up of Applications-ready Practical Y-Ba-Cu-O Coated Conductors

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***Abstract*--$YBa_2Cu_3O_x$ (YBCO) coated conductors have been produced in 100 m lengths in pilot scale facilities established at SuperPower. In addition to scaling up coated conductors to long lengths with high critical current, we have modified the basic conductor for enhanced in-field performance and low ac losses. In addition, our coated conductors have been produced in practical configurations in 4 mm widths and with a surround copper stabilizer. The conductors were slit first to 4 mm width and then subjected to electroplating to apply the copper stabilizer. Mechanical and electrical properties of the complete conductor have been elaborately tested. 61 m of 4 mm wide, surround copper stabilized conductor was provided to Sumitomo Electric Industries who fabricated a 1 m cable using the conductor. The cable exhibited the lowest ac losses reported with HTS conductors. SuperPower also fabricated a pancake coil with 7.4 m of coated conductor, which generated a maximum magnetic field of 0.28 T at 77 K.**

***Index Terms*—stabilizer, magnetic field, ac losses, narrow conductor, cable, coated conductor**

I. INTRODUCTION

SuperPower is scaling up $YBa_2Cu_3O_x$ (YBCO) coated conductors for use in electric power, military, and industrial applications. Over the last two years tremendous progress has been made in our scale up program, and full-fledged manufacturing of coated conductors is expected to be imminent. In addition to meeting the threshold of 100 m lengths of conductor with a critical current of 100 A/cm-width, we have been working towards fabrication of applications-ready practical coated conductors. Such coated conductors would possess excellent performance in a magnetic field, low ac loss characteristics, be of appropriate dimensions (preferably 4 mm wide), and be protected with a copper stabilizer. For this purpose, we have developed a rare-earth substituted composition that yields high critical currents in high magnetic fields at liquid nitrogen temperature. We have also initiated photolithographic striation of the coated conductor to reduce ac losses. Further, we have brought a slitting tool on line in our clean room operations to routinely slit 10 mm or 12 mm wide tapes to 4 mm widths. We have also developed an electroplating technique to apply copper stabilizer which completely surrounds the conductor after it is slit to 4 m width. In this article, we report details of our scale up of applications-ready practical coated conductors. We also present results from a prototype cable and a pancake coil constructed with our coated conductor.

II. SCALE UP TO 100 M LENGTHS

In order to scale up to 100 m long coated conductors, every single process step should be capable of handling a minimum of 100 m lengths. Polishing of Hastelloy-C substrates is conducted in a preproduction-scale electropolishing facility at SuperPower. Over 85 tapes in 100 m lengths have been polished in this facility at a linear speed of 20 to 60 m/h. 90% of the 85 polished substrates exhibit an average surface roughness less than 1.5 nm. Surface roughness is measured on-line in the electropolishing facility in 1 mm intervals.

Deposition of buffer layers on the electropolished substrates is conducted in a Pilot Ion Beam Assisted Deposition (IBAD) facility. This facility has been fitted with dual 66 cm long ion sources which provide a deposition zone 60 cm in length and 7 cm in width. In order to maximize the linear speed of the IBAD process, we use a helix tape handling system. In addition to increased linear tape speed, the helix tape handling system enables uniform deposition over a 7 cm width. In-plane texture measurements of the IBAD layer were obtained rapidly in 0.25 m intervals over 100 m lengths using a novel X-ray diffraction tool [1]. Figure 1 exhibits in-plane texture measurements obtained on six 100 m long IBAD tapes fabricated in our Pilot IBAD facility. It can be seen from the figure that low texture values can be reproducibly achieved uniformly over 100 m lengths. The average in-plane texture over 100 m long tapes ranged from 10.2 degrees to 10.8 degrees. The standard deviation of the in-plane texture over 100 m long tapes ranged from 2% to 3%. These values indicate the robustness of the IBAD process to fabricate 100 m lengths.

We recently reported YBCO deposition on 100 m long IBAD tapes. We have achieved 70 A/cm-width end-to-end

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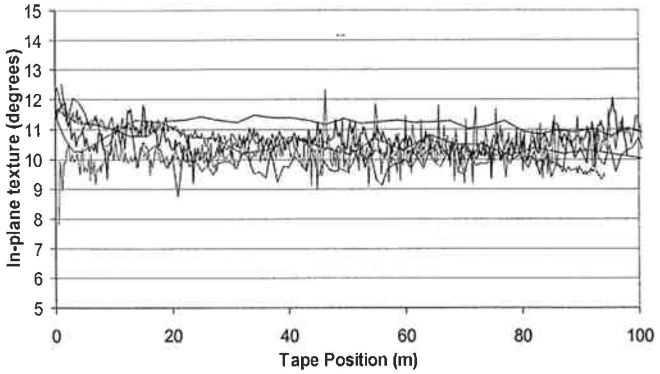

Fig.1. In-plane texture measurements obtained every 0.25 m of six 100 m long IBAD tapes. The texture of the 100 m tapes is found to be uniform and reproducible.

over 100 m as well as 105 A/cm-width end-to-end over 57 m [2]. These results represent the highest performance in terms of ampere-meter demonstrated in coated conductors.

II. IMPROVED IN-FIELD PERFORMANCE

Several applications of HTS involve operation in magnetic fields of 1 T and higher. Typically, the critical current of YBCO coated conductors drops by a factor of 7 to 10 from its zero field value at 77 K when a field of 1 T is applied parallel to the c-axis. We recently demonstrated that improved critical currents can be achieved in high magnetic fields by Sm substitution in YBCO [3]. Sm-substituted coated conductors exhibit only a factor of 4 to 5 drop in critical current from its zero-field value at 77 K and 1 T. Using Sm-substituted YBCO with a critical current value of 407 A/cm-width at zero field and 77 K, we were able to achieve high critical currents at 1 T and 77 K over a wide range of field orientations as shown in figure 2. Figure 2 reveals critical current values of 147 A/cm-width at B || a-b and 86 A/cm-width at B || c. The high critical current at B || c is possible because of a pronounced peak in critical current in this field orientation, possibly due to correlated defects. Another interesting feature in figure 2 is that a high critical current value of 65 – 67 A is obtained over a wide range of intermediate field orientations (25 to 80 degrees). This feature is important from the viewpoint of designing HTS coils, which will be subjected to magnetic fields over a wide range of magnetic field orientations.

II. LOWER AC LOSS CONDUCTOR

AC losses are another important property that will affect the use of HTS in practical applications especially those involving high frequencies or high magnetic fields. The only technique shown to date to result in lower ac losses in coated conductors is striation of the HTS layer into fine filaments. Striating the conductor reduces the effective width which is expected to result in lower hysteretic losses. IBAD-based conductors offer specific advantages in development of a low ac loss conductors. The substrates used in IBAD-based conductors are highly resistive and non magnetic, which lead to low eddy current losses and low ferromagnetic losses respectively. IBAD-based conductors are advantageous to be used in development of a striated conductor too. Because of the narrow filaments in a striated conductor, the grain size of the HTS grains need to small in order to avoid percolation problems associated with conductors with large grains [4]. Since the grain size of YBCO films deposited on IBAD layers is of the range of a micron, no pinch-offs are expected even with narrow filaments. While striated conductors prepared by laser patterning have yielded lower ac losses [5], it is questionable if this technique can be scaled up for industrial manufacturing. Hence, we evaluated an industrial process for striating coated conductors, namely photolithography. Photolithography is widely used in a reel-to-reel mode in the flex-circuit industry and the slowest step in this process is about 50 times faster than laser patterning. We patterned several conductors, directly on the HTS layer as well as through the silver cap layer. Filament sizes and filament spacing of 100 microns each have been produced. An example is shown in figure 3. We confirmed that negligible losses in critical current are incurred in the striated conductor.

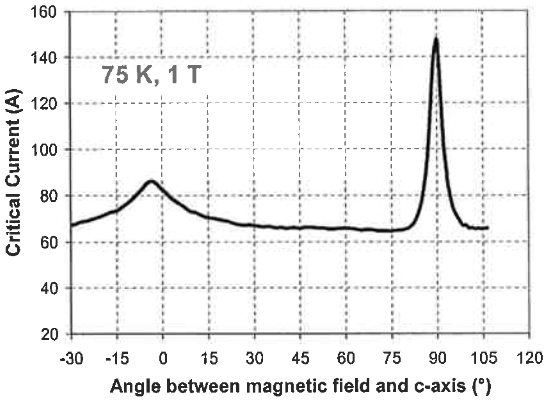

Fig. 2. Angular dependence of critical current of Sm-substituted coated conductor at 1 T, 75 K.

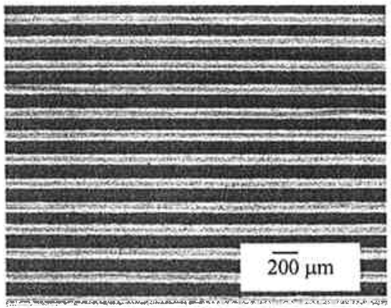

Fig. 3. Micrograph of a striated conductor prepared by photolithography.

Figure 4 compares the ac losses measured b an inductive technique at Brookhaven National Laboratory on unstriated conductors and conductors striated by photolithography. The striated conductor had 300 micron wide filaments spaced 100 microns apart. It can be seen from the figure that the striated conductor exhibits lower ac losses over the entire range of magnetic fields used. At 0.1 T, the ac loss of the striated conductor is a factor of 4.5 lower than that of the unstriated conductor.

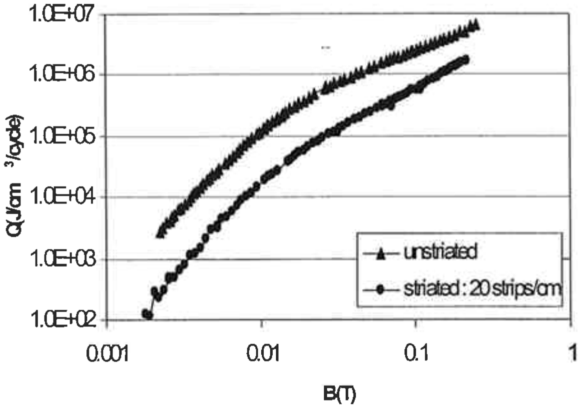

Fig. 4. Comparison of ac losses of unstriated conductor and conductor striated with 300 micron wide filaments spaced 100 microns apart.

III. ELECTROPLATED COPPER STABILIZER

Copper stabilizer application on coated conductors is important to provide quench stability and a current shunt around defects. We have developed an electroplating process to apply copper stabilizer on coated conductors. A key advantage of electroplating is complete coverage of the conductor on all sides in a single pass i.e. a surround stabilized conductor. Figure 5 shows a cross section of a coated conductor with a surround copper stabilizer. In this case, 20 microns of copper completely encases the conductor.

In order to examine the efficacy of the copper stabilizer, we conducted over-current measurements both at SuperPower and at MIT. Figure 6 exhibits results from over current measurements conducted at MIT with pulsed currents. Using 300 ms pulses where the current was increased in steps, it was found that the copper-stabilized conductor did not experience any substantial drop in critical current until it was subjected to current levels 9 times the critical current.

Fig. 5. Cross section of a coated conductor with surround copper stabilizer applied by electroplating.

IV. SLITTING

Coated conductors need to be fabricated in narrow widths, preferably 4 mm in order to be used in cable applications. Typically, coated conductors fabricated by most institutions are 10 mm in width and hence the need for slitting the conductor. Since our conductor configuration uses a surround copper stabilizer, we slit our conductor directly on the silver cap layer.

Figure 8 displays the critical current measured over an 8 m long conductor before and after slitting, and after copper stabilizer application. The critical current values shown are the normalized sum of the critical currents of both 4 mm wide conductors slit from a parent 10 mm wide conductor. It can be seen from the figure that the critical current of the 8 m long conductor degraded by only 1% after slitting and was not degraded at all after electroplating. This success enables us to slit our conductors directly on the silver overlayer.

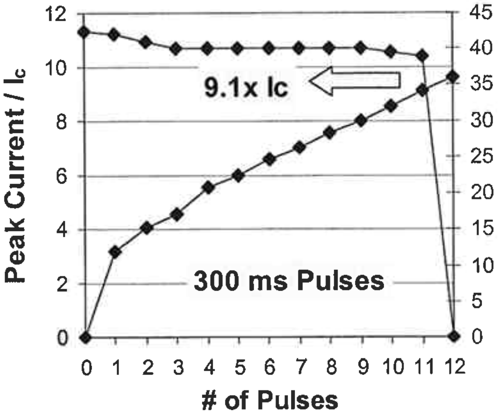

Fig. 6. Critical current measured at increasing peak currents applied in 300 ms pulses on coated conductor with surround copper stabilizer.

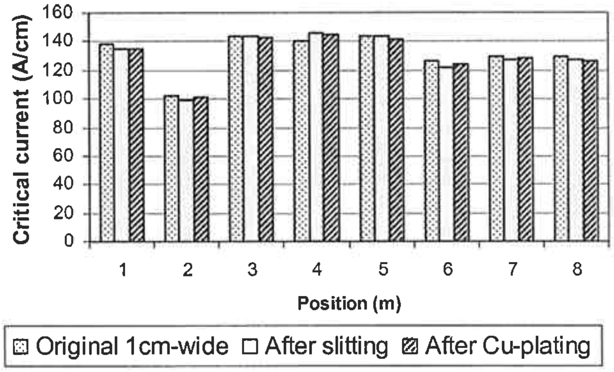

Fig. 7. Critical current distribution of an 8 m long coated conductor before and after slitting and after electroplating copper stabilizer.

IV. 1 m COATED CONDUCTOR CABLE

As a part of the Albany Cable Project, we worked with Sumitomo Electric Industries to fabricate a 1 m long coated conductor cable. We provided 61 m of 4 mm wide conductor with surround copper stabilizer for this purpose. 48 segments, each 1.2 m long were used to fabricate the cable. The 61 m of conductor was subjected to rigorous testing including measurements of critical tensile stress, bend strain in compressive and tensile modes, spiral winding, and width and thickness every 0.2 m before and after a hermetic test. Critical currents were measured before and after slitting, and after copper stabilizer application, and after hermetic test. Results from these rigorous tests are summarized in Table I. The specifications for the mechanical properties shown in the Table were defined for a critical current retention of 95% of the critical current of the conductor without any mechanical stress or strain. It can be seen from Table I that all performance requirements for the conductor were met or exceeded by a wide margin. The successful results from the hermetic test demonstrate the advantage of complete encasement of the HTS by the surround copper stabilizer.

TABLE I
PERFORMANCE DATA OBTAINED FROM 4 MM WIDE COATED CONDUCTOR WITH SURROUND COPPER STABILIZER

Property	Specification	Performance
Critical Tensile Stress	150 MPa	350 MPa
Minimum bend diameter (tensile)	100 mm	25 mm
Min. bend diameter (compressive)	100 mm	11 mm
Spiral winding	16 mm mandrel with 130 mm pitch	Met specification
Hermetic test (exposure to liquid nitrogen for 24 hours at 10 atm.)	No change in Ic or thickness	All 61 m met requirement

A photograph of the 1 m long cable is shown in figure 9. The coated conductors were wound around a 16 mm core with the HTS layers in tension. The critical current of the cable was measured to be 2150 A, which is essentially identical to the calculated value based on the critical current of individual conductors. The fact that no loss in critical current was experienced even though the HTS conductor was wound in tension over a small former is a good indication of the robustness of our conductors.

AC loss measurements were conducted on the 1 m cable fabricated with the conductor wound on a metal former and the results are shown in figure 11. Since no shielding layers were used, it was suspected that the eddy current losses in the metal former were the main contributor for the losses. Hence, the conductors were unwound and rewound on a FRP former and ac losses measured again. The results shown in figure 10 indicate ac loss values of 0.1 W/m and 0.4 W/m with FRP and metal formers respectively at a current level of 1000 A_{rms}, which corresponds to a peak current to critical current value of 0.67. These values are a factor of 5 to 20 lower than that reported in a previously made cable using coated conductors.

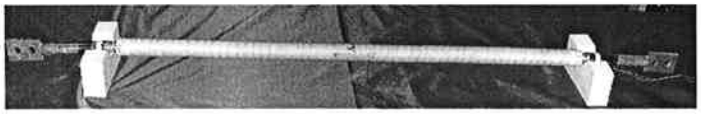

Fig. 8. Photograph of an 1 m long cable fabricated with 4 mm wide, copper stabilized coated conductor.

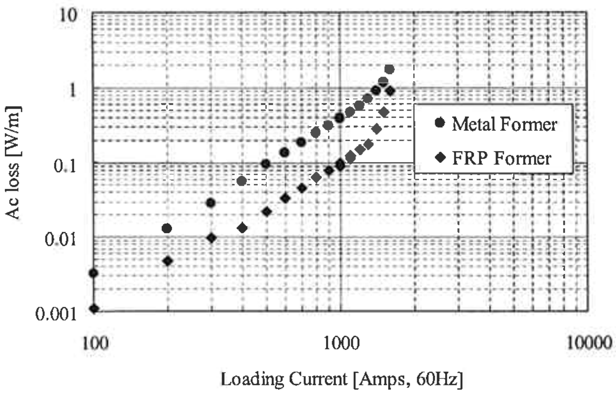

Fig. 9. AC loss measurements obtained from 1 m cable with conductor wound on metal and FRP formers.

VI. PANCAKE COIL WITH COATED CONDUCTOR

We also fabricated a pancake coil with 7.4 m of coated conductor with a small internal diameter of 14 mm. The coil consisted of 83 turns and a photograph is shown in figure 11. The critical current of the coil was 55 A at 77 K, which is about the expected value considering the field generated by the coil. Axial magnetic field measurements were conducted in the coil and the results are shown in figure 12. It can seen from the figure that the coil generated a maximum field of 0.28 T at 77 K.

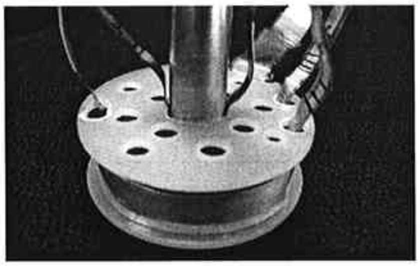

Fig. 10. Photograph of pancake coil fabricated with 7.4 m of coated conductor..

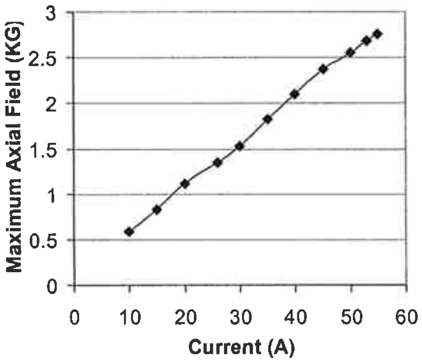

Fig. 11. Maximum axial magnetic fields generated by the pancake coil

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REFERENCES

[1] V. Selvamanickam, J. Reeves, and D. E. Peterson, U.S. Dept. of Energy Annual Peer Review, Washington D.C., July 17-19, 2002.

[2] Y. Li, J. Reeves, X. Xiong, Y. Qiao, Y. Xie, P. Hou, A. Knoll, K. Lenseth, and V. Selvamanickam, *IEEE Trans. Appl. Superconductivity*(this volume)

[3] V. Selvamanickam, Y. Xie, J. Reeves, and Y. Chen, *MRS Bulletin,* Vol. 29, pp. 579 – 582 (2004).

[4] E. Specht, *Supercond. Sci. & Technol.* Vol. 13, 592 (2000).

[5] C. B. Cobb, P.N. Barnes, T. J. Haugan, J. Tolliver, E. Lee, M. Sumption, E. Collings, C. E. Oberly, *Physica C.*Vol.382, pp. 52-56, (2002).