Second-generation HTS Conductor Design and Engineering for Electrical Power Applications

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***Abstract*—Besides critical current and conductor length, thermal stability, mechanical properties and ac loss characteristics of second-generation (2G) HTS wire are very important performance parameters to electric power device applications. Each application sets specific technical requirements on conductors. The properties of the practical 2G HTS wire manufactured at SuperPower, Inc. have enabled satisfactory performance in a number of demonstration devices including cable, high-field magnetic coil and fault current limiter. Yet, effort is being made to develop new conductor structures and configurations toward further enhanced performance in order to extend the potential of 2G HTS wire over a wider application range. This paper describes a variety of newly developed configurations: striation, narrow width, low-resistance joints and high quality insulation. The performance of wire with new configurations will promote the wide use of 2G HTS wire.**

***Index Terms*—High-temperature superconductors, Superconducting devices, Power systems, Electric variables measurement, AC machines, Superconducting magnets, Insulation, Superconducting cables, Fault current limiters**

I. INTRODUCTION

SECOND-generation high-temperature superconducting (2G HTS) wire, namely $YBa_2Cu_3O_{7-\delta}$ (YBCO) coated conductor, has great potential for commercialization and utilization as an engineering conductor for many real world applications such as transmission cables, superconducting magnets, fault current limiters, motors and generators. The most significant benefit from the wide use of 2G HTS wire in those real-world applications is energy savings from improved efficiency. For the past few years, tremendous progress has been made in 2G HTS wire technology development and manufacturing. The leading organizations in the world have just reported their latest achievement in the scale-up of 2G HTS wire technologies at the 2008 Department of Energy Annual Peer Review Meeting [1]. SuperPower, Inc has crossed the 1 km single piece length threshold and established a new world record performance of more than 200,000 amp-meters. Fujikura Ltd has also made 500 m long wires with performance as high as 170,023 amp-meter. All of these achievements have encouraged the acceleration of the worldwide effort to develop superconducting devices with 2G HTS wire. At SuperPower, Inc., in addition to meeting the piece length and critical current performance requirements for the wire, we have been working to ensure the readiness of practical coated conductors for a variety of applications through post-HTS processing. Up to now, our standard product configuration has included wire with and without surround copper stabilizers (SCS and SF types, respectively), two different tape widths (12 mm and 4 mm), and two different substrate thicknesses (50 and 100 micron). These wires are being delivered to end users and have demonstrated superior performance in prototype devices and in live-grid applications as well. In order to achieve further market penetration, besides improving the production throughput and yield to reduce the cost/price ratio, SuperPower has also been working to further improve the critical current of the wire, especially in magnetic field, and to improve conductor configurations for application-specific environments. In this paper, we will provide an overall description of our efforts and results in 2G HTS conductor design and engineering for ac reduction, narrow wires, joints, SFCL application and insulation.

II. AC TOLERANT CONDUCTOR

Since 2G HTS wire come off of the production line in tape form, the high hysteretic loss when wires are exposed to alternative magnetic field perpendicular to the wire surface, (i.e., face-on situation, due to the high aspect ratio or wide tape width) will adversely affect the use of HTS in practical applications [2]. Striation of the HTS layer into fine filaments has been shown to be an effective way of lowering ac losses in 2G HTS wire. Striating the conductor to reduce the effective width, that is expected to result in lower hysteretic losses, has thus far been demonstrated on short samples by many institutions. SuperPower developed a photolithography technique and was able to achieve a fine filament/trench structure of about 100/25 μm. The samples with such a fine filament/trench structure showed ac loss reduction at a factor of 73 according to the magnetization measurement carried out at the Ohio State University [3]. An innovative method was also developed to make multifilamentary wires even with copper stabilizer at a thickness of ~ 20 μm as illustrated in Figure 1.

The sample length in the photolithography approach was about tens of centimeters; however, further scaling up was

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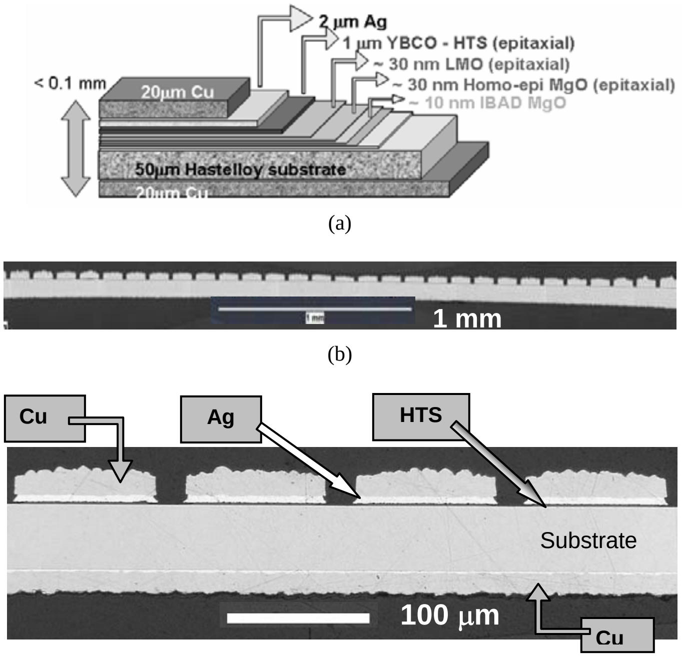
found to be a challenge. Figure 2 shows SEM images of the cross sections at the edges of the filaments of two samples photolithographically striated at different conditions. Both show residues at the trenches and undercut at the filaments. The residues in the trenches increase ac losses and the undercut in the filaments decrease the critical current (I_c). It has been found that the repeatability of the process is a major challenge for scale-up to long lengths.



(a)

(b)

(c)

Fig. 1. Filamentization on short 2G HTS wire samples to reduce ac loss achieved through photolithography patterning: (a) Layout of the multilayer structure of a SuperPower® SCS type of 2G HTS wire; (b) Cross-sectional view of a filamentized 2G HTS wire; (c) a close-up view of (b) clearly showing that the entire multilayer structure on the HTS side of has been striated. Each filament is 100 μm wide containing copper, silver, HTS layers. The separation of the filament is ~20 mm; only the buffer layers remain in the trenches.

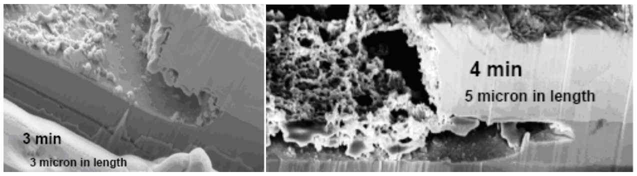


Fig. 2. SEM cross-sectional views of the boundary areas at the edges of the filaments. The cross-sections were obtained with a Focused Ion Beam (FIB) cut. Both photo images show some residue at the trenches and undercut at the filaments at two different etching conductions: 3 minutes (left) and 4 minutes (right) etching time. The latter was done using a more diluted etchant.

Facing this challenge, we developed a new industrial process, and we are current applying this technology to make striation on 4 mm wide tapes with five filaments each 650-800 μm wide and four trenches each 100-125 μm wide. A short sample showed ac reduction at a factor of five as tested with a magnetization (pick-up coil) method (photo at the upper part of Figure 3). This new industrial process is repeatable and has allowed us to scale up the length to 15 m. The photo at the lower part of Figure 3 shows a 15 m long wire with continuous filamentization over the entire length wound on a mandrel. Using those long multifilamentary wires, coils have been made to compare with those made with monofilamentary wires. The test results of the coils have been reported elsewhere [1].

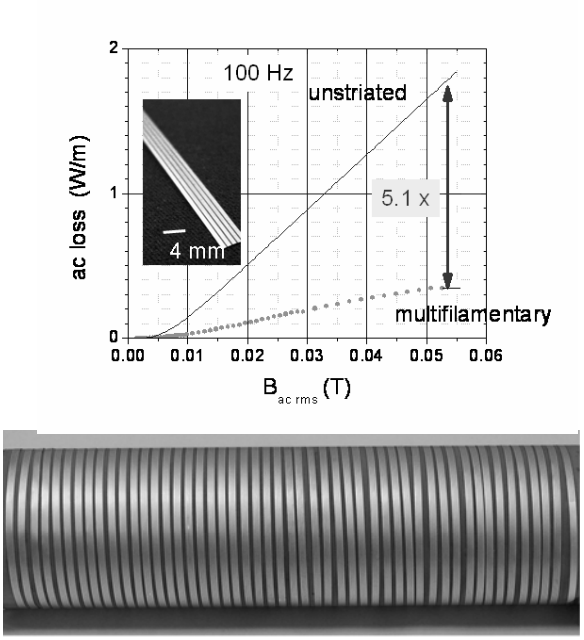


Fig. 3. A reliable industrial process for striating 2G HTS wire into a multifilamentary structure has been developed at SuperPower: short samples 4 mm wide with five segments show 5.1× ac loss reduction as tested in a magnetization measurement in applied field (chart, upper part); 15 m long wire with continuous filamentization over entire length (photo, lower part).

Narrow wires will yield lowered ac loss too, not only as individual wires but also allowing more flexibility in wire assembly, e.g., twisting and stacking [4, 5]. Narrow widths are obtained from a slitting process with a commercial machine. As one demonstration of excellent wire properties, SuperPower® 2G HTS wires show minimum I_c reduction through the slitting process [6]. By altering the slitting knife set configuration, we have successfully fabricated wires in a variety of widths, 8, 6, 4, 2, and 1 mm, with 100% utilization of the 12 mm wide tape.

SuperPower® 2G HTS wire is also suitable to be used for ROEBEL cable; with only 3% loss in I_c from wire to ROEBEL cable [7]. In ROEBEL cable, strands are fully transposed and thus result in lower ac losses. In the fabrication of ROEBEL cables, wires are subjected to severe mechanical cutting at sharp angles and current follows not only along the length of the wire but also across the width at an angle ~ 30^o. Degradation in I_c in a ROEBEL cable can be due to mechanical defects caused by cutting or non-uniformity of current flow across width. It is useful to separate the two mechanisms and study current flow across width by itself. The approach we took is to pattern the 12 mm wide tape to mimic the situation of current flow in a ROEBEL cable strand. At the top of Figure 4, a 50 cm long 12 mm wide 2G wire was patterned into multiple segments for measurements of I_c at different angles of current flow. The chart in Figure 4 shows that there is no systematically discernible I_c reduction in intermediate angles that are employed in ROEBEL cable fabrication. The data is somewhat scattered; further data collection is underway to get useful statistics.

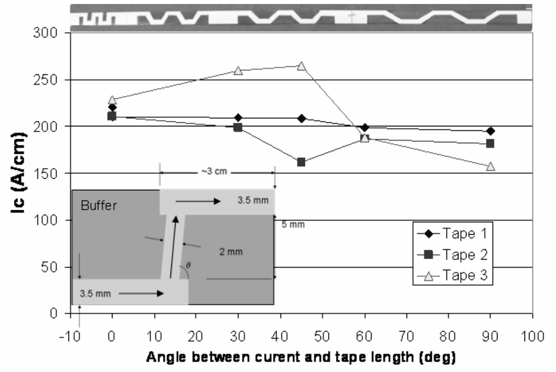


Fig. 4. I_c as function of angles between the current and tape length. Three 2G HTS wires were patterned into multiple segments (as illustrated by the photo on the top) for measurements.

III. JOINTS

2G HTS wire is routinely produced with piece lengths of at least few hundreds meters at SuperPower. Since some applications call for kilometer-lengths, joints are needed to get beyond the currently available joint-free lengths and these have to be as mechanically robust as the non-jointed regions so that these long jointed wires may be widely used.

To develop the technique, joints were first fabricated in a lab setting and current-voltage (I-V) curves over the joined regions were measured to compare with the original wires. Commercial solder materials such as Pb37Sn63 and Indium were used to make the joints and the processing temperature was controlled below 250^{o}C to avoid the escape of oxygen from the YBCO lattice. While the I_c of the spliced region is maintained the same, there is always a linear slope on the I-V curves before the HTS layer transitions to normal and it is called “joint resistance” in units of $n\Omega\text{-cm}^2$ over the joints. The joints were also subjected to a bending test in which they were bent over a mandrel at room temperature and held in position when immersed into liquid nitrogen for an I-V characteristic test. The layout of a face-to-face lap joint (it is easily understandable that face-to-face joints yield the minimum contact resistance compared to other configurations) was shown on the top of Figure 5; the test result of a typical lap joint 3.5 cm long with 4 mm wide wire with 20 µm thick surround copper stabilizer. There is no I_c degradation when the joints were bent over mandrels of different diameters, 2, 1.5 and 1 inches, respectively. The contact resistance of the joint is 43 $n\Omega\text{-cm}^2$ initially. A slight decrease in joint resistance is shown when the lap joint was bent, the reason for which is unclear at the point but could be attributed to the thinning of the solder material between the two HTS layers when the joined region was bent over the mandrel.

As the second development step, a production operation was developed to make consistently high-quality joints to fulfill wire orders from customers. To complete a recent wire delivery that required 1,200 m of 2G wire with 11 splices for a coil application, the mechanical robustness of the joints made in the production operation was also established since the joined wire had to be moved through 4” and 2” diameter rollers in the 5 m long transport test rig at a speed of up to 400 m/h to measure the I_c of the entire wire length and resistance of all regions.

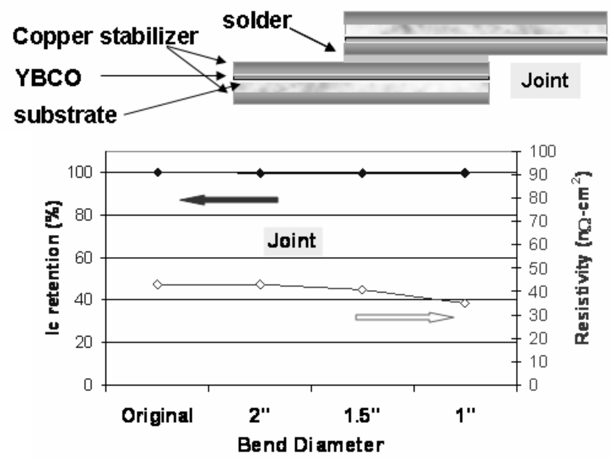


Fig. 5. A face-to-face lap joint showed very low contact resistance no I_c degradation when the joint was bent over mandrels of different diameters: 2, 1.5 and 1 inches, respectively.

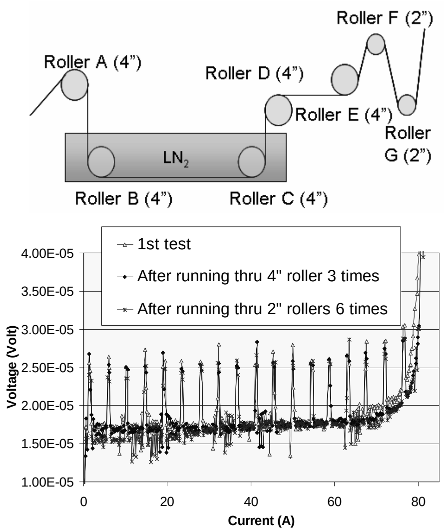


Fig. 6. Mechanical robustness of face-to-face joints made in a production operation: there was no degradation shown from I-V curves measured before and after the joints were moved through the roller assembly on a reel-to-reel I_c test rig many times at a speed of 400 m/h.

To test the mechanical robustness of the splices, we placed them in the I_c test rig to measure the I-V curves (kept flat) and then moved through the roller assembly (top of Figure 6) on the rig repeatedly many times and tested the I-V curves again. As shown in Figure 6, there was no degradation after a joined region had been run through the 4 inch diameter roller assembly three times and the 2 inch one six times. After the completion of the tests, 12 segments of 2G HTS wire were joined together with 11 lap joints to a length of 1218 meters. The I_c profile was successfully tested over the entire length and I-V curves over all 11 lap joints were collected as well. Figure 7 depicts the I-V curves of all sections (5 m long as tested) containing the joints, that show smooth transitions at their respective I_c (upper chart) and small joint resistance of 33 nΩ. The cause of one of the 11 joints having relatively high joint resistance is under investigation.

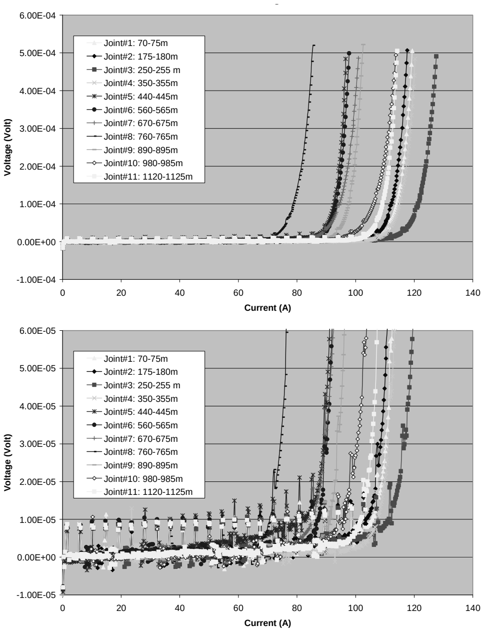


Fig. 7. I-V curves of 11 lap joints on a 1,218 m long 2G HTS wire for a coil application. Upper chart: all joints show smooth transition at their respective I_c. Lower chart: the slopes before transition show that 10 of the 11 splices have contact resistance around 33 nΩ; one has resistance around 100 nΩ, but still below specs for that specific coil application.

IV. INSULATED 2G HTS WIRE

Insulation on 2G HTS wire is needed, especially for coil applications. Depending on the specs, layer coating and helical winding are two choices to obtain insulation at different voltage levels. Recently, we brought in a helical wrapping insulation machine specifically designed for 2G HTS wire to enable in-house fabrication of insulated wire. The system is capable of insulating both 12 and 4 mm wide wire as shown in the two photos at the upper part of Figure 8. The insulation materials are polyimide films of different thicknesses, e.g., 0.0125 mm and 0.025 mm, with adhesive materials (silicon or acrylic) or without. The breakdown strength of polyimide film is about 3500 V at 0.025 mm thickness.

Wires must not suffer I_c degradation after insulation. Since the process is done at room temperature atmosphere, degradation could only be caused by mechanical damage. To ensure the quality of the insulated wire, our quality control procedure has been extended to cover this operation. Since the insulated wire is accessible for transport I_c measurement, a non-contact I_c measurement is applied before and after insulation as shown in the chart at the lower part of Figure 8. Although the overall I_c is slightly lower due to enlarged HTS film to measurement sensor distance, there are no new I_c drops that would be associated with mechanical damages.

V. SUMMARY

SuperPower® 2G HTS wire is being further developed in a variety of configurations through conductor design and engineering: striation, narrow width, low-resistance joints and high quality insulation. These new configurations will make the wire more suitable for real-world electric power applications and promote the wide use of 2G HTS wire. Angular dependence of I_c also shows suitability for ROEBEL conductor fabrication.

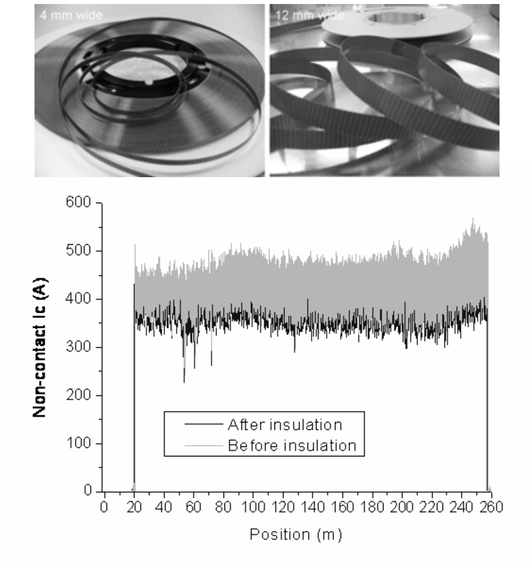


Fig. 8. SuperPower® 2G HTS wire (4 mm wide and 12 mm wide) insulated with polyimide films (photos at the top). There is no degradation shown from a non-contact I_c measurement before and after insulation (lower chart).

REFERENCES

[1] V. Selvamanickam and Y. Xie, “Progress in Scale-up of 2G HTS Wire at SuperPower” and Y. Yamada, “Global Progress in HTS - Japan Update”, *2008 Dept. of Energy Annual Review, Superconductivity for Electrical Systems*, July 29-31, 2008, Arlington, VA.

[2] M. Sumption, “AC Loss in Striped (Filamentary) YBCO Coated Conductors Leading to Designs for High Frequencies and Field-Sweep Amplitudes”, *Superconductor Science and Technology.* 2005, vol. 18, pp. 122–134.

[3] V. Selvamanickam, Y. Xie and J. Reeves, “Progress in Scale-up of 2G HTS Wire at SuperPower”, *2006 Dept. of Energy Annual Review, Superconductivity for Electrical Systems,* July 25–27, 2006, Washington, DC.

[4] Y. Xie, X. Zhang, Chapter 16 “*Development of 2nd-Gen HTS wires for ac applications at SuperPower, Inc*” in Book “*Flux Pinning and AC loss Studies on YBCO Coated Conductors*” edited by M. Paranthaman and V. Selvamanickam, Nova Science Publishers, Inc. New York, 2007.

[5] R. Duckworth and D. van der Laan, “Conductor Design for HTS Applications”, *2007 Dept. of Energy Annual Review, Superconductivity for Electrical Systems*, August 7-9, 2007, Arlington, VA.

[6] V. Selvamanickam, *et al.*, “Scale up of Application-ready Practical Y-Ba-Cu-O Coated Conductor”, *IEEE Trans. Applied Superconductivity*, vol.15, No.2, pp2596-2599, June 2005.

[7] W. Goldacker, A. Frank, R. Heller, S.I. Schlachter, B. Ringsdorf, K.-P. Weiss, C. Schmidt, S. Schuller, “ROEBEL Assembled Coated Conductors (RACC): Preparation, Properties and Progress”, *IEEE Trans. Applied Superconductivity,* vol. 17, No. 2 pp. 3398-3341, June 2007.