

# The Development of Second Generation HTS Wire at American Superconductor

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**Abstract**—Second Generation (2G) YBCO High Temperature Superconductor wire, based on the RABiTS™/MOD process, is now being produced in continuous lengths at American Superconductor (AMSC) using a full-scale, reel-to-reel manufacturing line. AMSC’s approach for manufacturing 2G wire is designed around a low-cost, wide-strip technology, in which a 4-cm wide strip is slit into multiple narrower wires, then laminated to metallic stabilizers producing a 3-ply wire called 344 superconductors. A major advantage of this approach is the ability to tailor the electrical, mechanical and thermal properties and dimensions of the final wire for specific applications and operating conditions. This allows the final wire properties to be tuned for targeted applications, including cables and fault current limiters, by tailoring the resistivity and thickness of the stabilizer layers. The superconducting properties of the MOD-based YBCO are also being improved by the introduction of thicker YBCO layers and improved flux pinning centers. This paper describes the present status of 2G wire manufacturing at AMSC, reviews present and projected performance of the 344 superconductors, and summarizes initial application demonstrations utilizing 344 superconductors.

**Index Terms**—2G wire, coated conductors, YBCO, RABiTS, HTS

## I. INTRODUCTION

SECOND generation (2G) high temperature superconducting (HTS) wires have moved out of the laboratory and are now being produced in the quantity, and with the performance, required for large-scale commercial application demonstrations. 2G wire is now supplanting first generation (1G) HTS wire, based on a multifilamentary composite in a silver matrix, in most HTS-based wire applications [1] – [3]. Two major advantages of the 2G technology pioneered by AMSC, over the first generation (1G) HTS wire, include lower cost and the ability to tailor the wire properties and dimensions for specific applications [4].

In this paper, we describe AMSC’s progress in transitioning the 2G wire process from an R&D “pre-pilot”-scale to high

volume, production-scale manufacturing and review the properties of the initial 2G HTS wire being produced in AMSC’s production-scale facility.

## II. AMSC’S 2G “WIDE-STRIP” MANUFACTURING PROCESS

AMSC’s approach to manufacturing 2G HTS wire is based on the RABiTS/MOD technology using a “wide-strip” manufacturing process [2], [4]. For initial operation of the full-scale production equipment, we have chosen to use 4-cm wide strips. The “wide-strip” manufacturing process, illustrated in Fig. 1, relies on the deformation-texturing of a metal alloy (Ni5at%W) substrate and recrystallization in a reel-to-reel system to form a cube-textured alloy template [5], [6]. The buffer layers, consisting of a 75 nm thick Y<sub>2</sub>O<sub>3</sub> seed layer, a 75 nm YSZ barrier layer and a 75 nm CeO<sub>2</sub> cap layer are deposited by high-rate reactive sputtering .

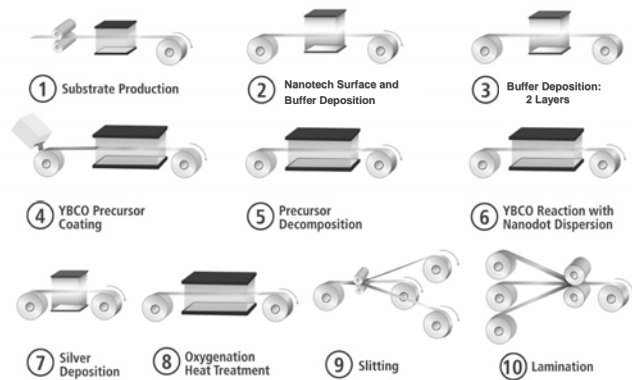


Fig. 1. Schematic illustration of the “wide-strip” manufacturing process for manufacturing low-cost 2G wire at AMSC.

A rare earth doped YBCO precursor film is slot-die coated onto the buffered substrate at a loading of 4800 mg Y(Dy<sub>0.5</sub>)Ba<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub>/m<sup>2</sup> of template (calculated thickness of 0.8 μm YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub>), pyrolyzed at <600°C and converted to an epitaxial YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> film at 750-800°C in a reel-to-reel system. The YBCO strip is capped with a Ag layer, and oxygenated at ~500°C. The Ag coated strip is then slit to the desired width and laminated between two metallic stabilizer strips to form the superconducting wire. The standard wire product, called 344 superconductors (Fig. 2), is prepared from a 4-mm slit ‘insert wire’ and has equivalent dimensions to the First Generation (1G) BSCCO HTS wire. The composition of the stabilizer strip is indicated by the addition of a letter to the wire name, i.e. 344B of brass and 344S for stainless steel.

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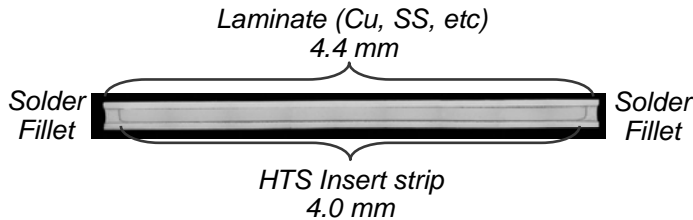


Fig. 2. Cross-section micrograph of AMSC's standard 2G HTS wire, called 344 superconductors.

The “wide-strip” process is designed to be inherently low-cost and has the flexibility to produce wire with varying dimensions and properties which can be tailored for specific applications, as illustrated in Fig. 3. The current production scale equipment is designed to process strips with a width up to 10 cm and length to 1 km; however, the initial operation of the equipment uses a 4-cm wide strip.

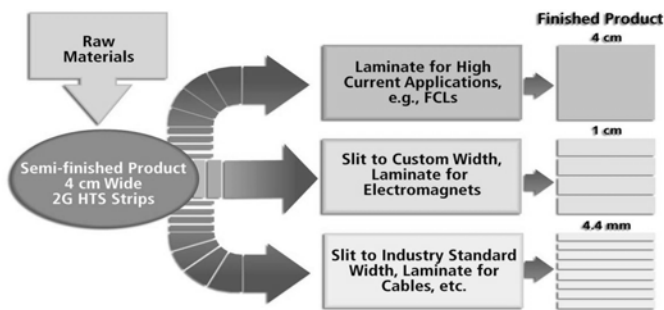


Fig. 3. AMSC's “wide-strip” process allows custom fabrication of 2G wire with dimensions and properties customized for specific customer applications.

Over the past 6 months, the “wide-strip” process has been fully implemented in production-scale equipment at AMSC with an installed capacity of over 500 km of 344 superconductors per year [7]. The demonstrated capacities for each key process step are shown in Fig. 4 for a process starting with a 4-cm wide NiW strip. As the market demand increases, the processing strip width will increase to 10-cm, resulting in a 2.5-fold increase in manufacturing capacity, without installation of additional equipment.

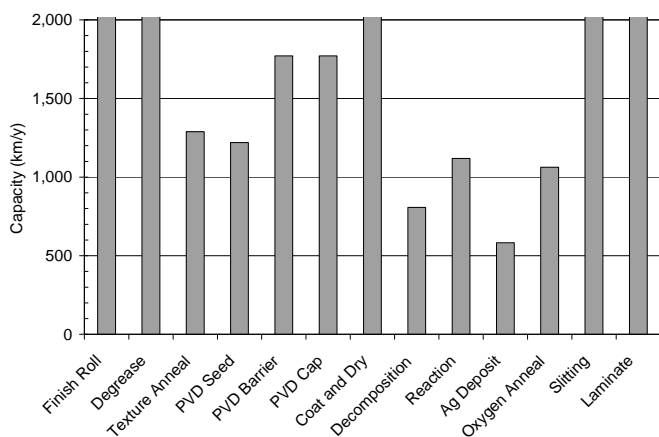


Fig. 4. Demonstrated annual capacity of each individual processing step in AMSC “wide-strip” process for manufacturing 344 superconductors. Annual capacities are based on a 4-cm processing strip width and include setup and maintenance time.

### III. 2G PRODUCTION QUALIFICATION

#### A. Benchmark Performance

AMSC's path to qualifying the commercial scale manufacturing process and equipment was to initially establish a commercial performance level in wires produced with the 4-cm “wide-strip” process in nominal lengths of 80 to 100 meters in R&D pre-pilot equipment and then to transition to production scale equipment capable of processing 4 - 10 cm wide strips in lengths to 1 km.

The benchmark performance level of material demonstrated in the pre-pilot equipment reached an  $I_c$  exceeding 100 A in a 344 superconductor (250 A/cm-w) as shown in Fig. 5 [4].

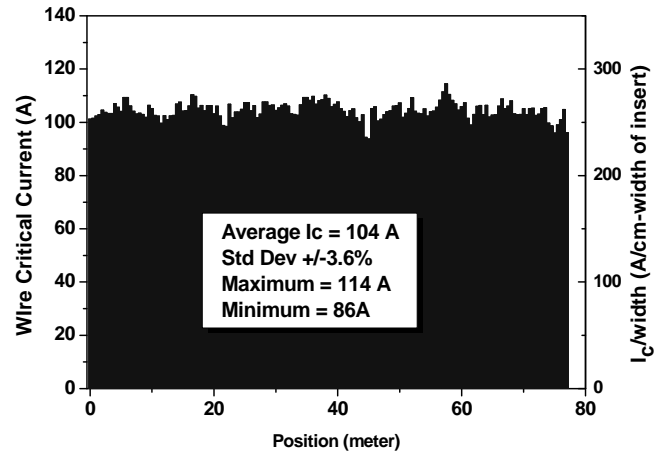


Fig. 5. Benchmark performance ( $I_c$  at 77K, self-field) of a 344 superconductors wire produced AMSC's in pilot manufacturing line ( $0.8 \mu\text{m}$   $\text{Y}(\text{Dy}_{0.5})\text{Ba}_2\text{Cu}_3\text{O}_y$  layer) [4].

#### B. RABiTS Template

The transition from the pilot to production-scale manufacturing required increasing the Ni5at%W batch size from approximately 300 lb to 5,000 lb with no change in uniformity of performance. The production-scale Ni5at%W batch is rolled to a 10-cm strip with a length of 1.2 km. Currently, this strip is then slit into 4-cm wide strips with a length of 600 meter before being used in the remainder of the process. Figure 6 shows the in-plane texture of the production scale Ni5at%W is slightly improved compared to the pilot scale material. The out-of-plane texture of  $\sim 6.5^\circ$  is comparable in both materials.

It was previously shown, with the pilot-scale buffer deposition process, that the out-of-plane texture of the  $\text{Y}_2\text{O}_3$  seed layer can be significantly enhanced relative to that of the Ni5at%W substrate by increasing the compressive strain in the  $\text{Y}_2\text{O}_3$  film [8]. This enhanced texture propagates through the buffer stack, leading to improvements in the  $J_c$  of the YBCO layer [9]. One approach to increase in the compressive strain is to increase the  $\text{Y}_2\text{O}_3$  deposition temperature. When this process was implemented in the production-scale equipment, the expected texture enhancement was obtained; however, the  $J_c$  of the HTS layer, after initially increasing, subsequently decreased with further improvements in the texture of the seed layer as shown in Fig. 7. This reduction in  $J_c$  was traced to a secondary texture in the  $\text{Y}_2\text{O}_3$  layer at the higher deposition temperatures. The undesirable texture was identified as

$Y_2O_3\langle 100 \rangle \parallel NiW\langle 110 \rangle$  texture where the  $Y_2O_3$  has a single axis epitaxy and is free to rotate around the axis. Operation of the production-scale process was optimized to maximize the texture enhancement while preventing the secondary texture formation.

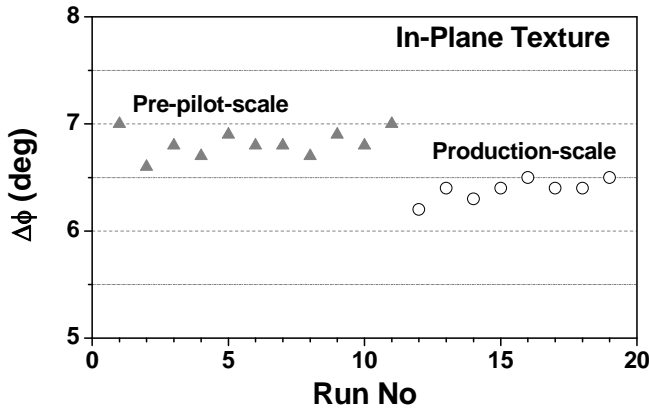


Fig. 6. Run chart showing improvement in the in-plane ( $\Delta\phi$ ) texture of the production-scale Ni5at%W substrate compared to the pilot-scale Ni5at%W substrate.

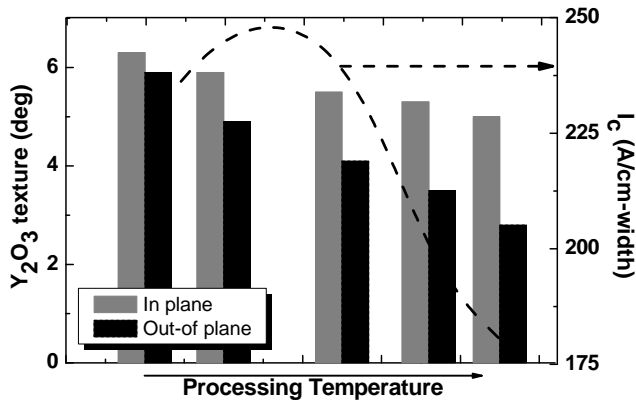


Fig. 7. Effect of processing temperature during reactive sputtering on in-plane and out-of-plane texture of  $Y_2O_3$  seed layer on the NiW substrate and corresponding effect on  $I_c$  of subsequent YBCO layer. Texture of starting Ni5at%W substrate:  $\Delta\phi: 7.3^\circ$  and  $\Delta X: 6.5^\circ$ .

Operation of the “wide-strip” process in the 200 – 500 meter length scale results in a stable process with minimal change in the texture of the template along the length or from run-to-run. This stability is shown in Fig. 8 which plots the average texture of the YSZ layer from the front and back of the long length tapes for a series of 20 runs all with lengths of 200 – 500 meters.

### C. Superconducting Layer

The HTS layer used in the initial production qualification consists of a Dy-doped YBCO layer with the composition  $Y(Dy_{0.5})Ba_2Cu_3O_{7.8}$ . The nominal YBCO thickness of the layer is  $0.8 \mu m$ . The composition and HTS processing result in the formation of a 3-dimensional microstructure consisting of nanoparticles and 124-type planar defects that can be optimized to control the pinning at various orientations of an applied magnetic field [10] – [12]. Figure 9 shows the angular field dependence of the 344 superconductors produced in the production-scale equipment has the same performance as achieved in the pre-pilot scale process.

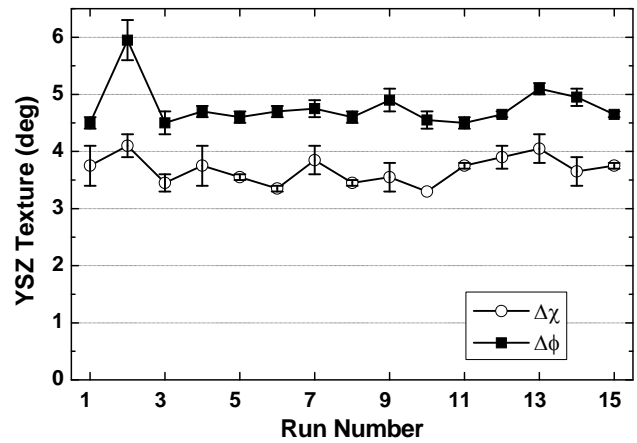


Fig. 8. Run chart showing average texture of the YSZ buffer layer on the  $CeO_2/YSZ/Y_2O_3/NiW$  template. Error bars represent difference between texture measured at the beginning and end of the 4-cm strip. Length of the 4-cm wide strips ranged between 200 – 500 m.

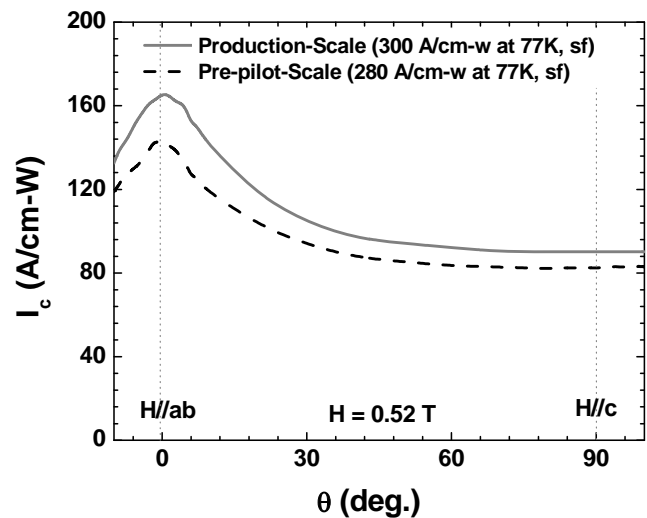


Fig.9. Angular dependence of the 344 superconductors wire produced in with the production-scale process is the same as achieved in the pre-pilot-scale equipment.

A critical requirement in the manufacturing of a 2G HTS wire for use in large-scale applications is the ability to precisely control the performance along the length, not just in self field, but also in the presence of an applied field at various field orientations. Figure 10 shows a plot of the transport  $I_c$  (77K, self filed) measured at 4-cm intervals along 10 meters of 344 superconductors. The self-field data show the presence of a drop in the  $I_c$  at approximately 1.2 m and periodic variations at a scale of  $\sim 2m$  along the length. Corresponding transport  $I_c$  measurements made in 0.5 T magnetic field, applied both parallel and perpendicular to the tape surface, show there is virtually no variation in the field dependence along the length of the wire. This shows that the 3-dimensional pinning microstructure is precisely controlled in the YBCO layer and that the observed  $I_c$  variations are solely due to cross-sectional variations in the wire and not to intrinsic variations on the YBCO properties.

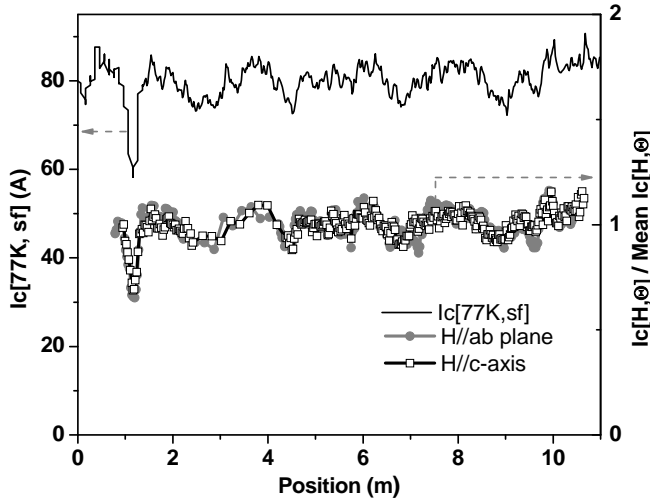


Fig. 10. Transport critical current measured at a 4-cm resolution along a 344 superconductors wire in self-field (77K) and the normalized  $I_c$  measured on the presence of a 0.5 T magnetic field oriented parallel and perpendicular to the 344 superconductor face. The normalized  $I_c$  is represented as  $I_c[H,\Theta] / \text{Mean } I_c[H,\Theta]$ .

#### IV. 344 SUPERCONDUCTORS PERFORMANCE

A primarily advantage of the “wide-strip” process is the ability to produce multiple wires, all with similar performance, from a single 4-cm wide strip. Figure 11 shows the  $I_c$  (77K, self-field) measured along the length of a 200 meter long 344 superconductors (top panel) and contour map showing the  $I_c$  along the length and width of the 4-cm strip (bottom panel). This contour map, constructed from the transport  $I_c$  measured along the length of each individual wire, shows the good uniformity across the 4-cm width and along the length of these initial wires. Although there are a few localized dips in the  $I_c$  map, the average  $I_c$  along the length of the individual wires are very similar as illustrated in Fig. 12. This single 200 meter strip produced 1.4 km of 344 superconductors, demonstrating the major cost and throughput advantage of the “wide-strip” technology.

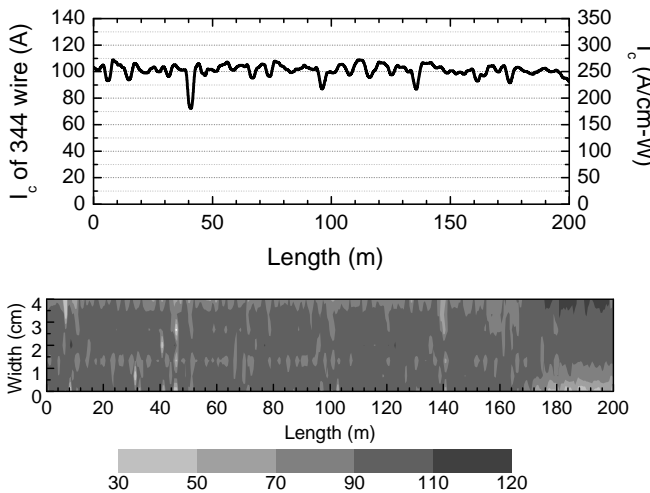


Fig. 11.  $I_c$  performance (top) of a 200 meter long 344 superconductors wire produced in AMSC’s production scale manufacturing line and contour map (bottom) showing  $I_c$  along the length and width of the 4-cm strip.

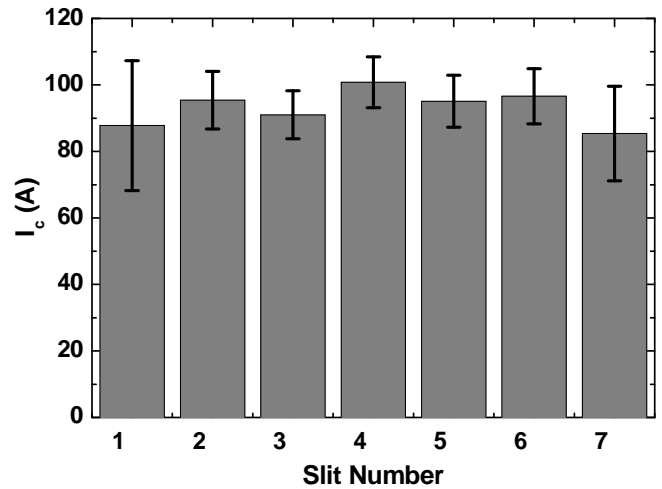


Fig. 12. Average  $I_c$  of the 7 individual 344 superconductors wires produced from the 4-cm strip shown in Fig. 11.  $I_c$ ’s were measured at a 1 meter length scale and error bars reflect variation in each individual strip.

Figure 13 shows the  $I_c$  (77K, self-field) measured along the length of a 100 meter long 344 superconductors wire. The wire achieved a minimum  $I_c$  of  $>105A$  over the entire length, matching the benchmark performance obtained with the pre-pilot equipment previously shown in Fig. 6. The  $I_c$  levels in the initial 344 superconductors production wires have been achieved with 0.8  $\mu\text{m}$  thick Y(Dy)BCO layers. It is projected that the  $I_c$ ’s in the 344 superconductors wires will reach 150 A when thicker (1.4  $\mu\text{m}$ ) YBCO films are incorporated into the production-scale process in late 2008.

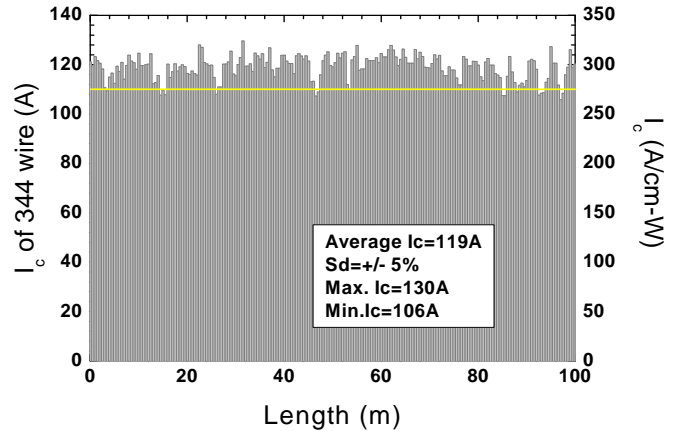


Fig. 13 Performance ( $I_c$  at 77K, self-field) of a 344 superconductors wire produced in the production-scale manufacturing line (0.8  $\mu\text{m}$   $\text{Y}(\text{Dy}_{0.5})\text{Ba}_2\text{Cu}_3\text{O}_y$  layer) [4].

#### V. 2G WIRE PRODUCTS AND PROPERTIES

A second major advantage of the “wide-strip process is the ability to customize the 2G wire width and stabilizer properties for the final product. 2G wires are currently being produced in the 344 superconductors with a variety of stabilizers, including copper, brass and stainless steel, to meet the requirements of specific applications including transmission cables, fault current limiters, coils and Roebel cables. Wires are also being produced in 1 cm widths for various coil applications such as fault current limiters and generators. The wider format allows higher currents in a

single wire and significantly reduces coil fabrication costs for the end user.

## VI. APPLICATIONS

The unique and customizable properties of AMSC's 2G HTS wire have resulted in a number of successful application demonstrations. In particular, 344S superconductors (stainless steel stabilizer) wires, which have a high heat capacity and high resistance stabilizer, have been used in a number of fault current limiter demonstrations.

A single-phase standalone fault current limiter with a nominal rating of 2.25 MVA at 7.5 kV (equivalent to a 13 kV three-phase) was demonstrated by Siemens and AMSC [13], while Hyundai demonstrated a single-phase standalone fault current limiter with a nominal rating of 8.3 MVA operating at 13.2 kV [14].

The unique properties of AMSC's 2G wires also allow fault current limiting functionality to be incorporated directly into HTS cables. This provides a significant potential benefit to the utilities including a reduction in the amount of copper and controlling system-wide fault currents without the need of additional standalone fault current limiters [2]. This approach, referred to as AMSC's Secure Super Grids™ System, is being developed in a joint program with AMSC, Southwire and Con Edison and sponsored by the US Department of Homeland Security. The concept has been successfully demonstrated in several meter long cables and is being targeted for installation in the New York City grid in 2010 [15].

## VII. CONCLUSION

The low-cost "wide-strip" manufacturing process for 2G HTS wire, based on the RABiTS/MOD technology, has been successfully implemented at AMSC in a full-scale production line. The production process is currently operating with a 4-cm strip width and has the demonstrated annual capacity of over 500,000 meters of 344 superconductors. The performance of the initial 344 superconductors produced in the production-scale equipment matches the benchmark performance of wires produced in the earlier pilot-scale process. A minimum critical current of >105 A (77K, self-field) has been achieved in 100 meter long 344 superconductor wires manufactured with a 0.8 μm thick Y(Dy)BCO film.

The flexibility of the "wide-strip" process and proprietary lamination technology allows the 2G wire to be customized for specific applications and delivered to customers in widths up to 4 cm.

The successful implementation of the "wide-strip" manufacturing process at AMSC is leading to a large increase in the quantity of 2G wire available for use in major application demonstrations. 2G wire from AMSC is currently being produced for applications including fault current limiters, cables and generators.

The successful development of a low-cost manufacturing process, along with planned improvements in performance, including the introduction of thicker YBCO films, provides a path to the low-cost manufacturing of 2G wire with performance exceeding 200 A (500 A/cm-width).

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## REFERENCES

- [1] R.M. Scanlan, A.P. Malozemoff, D.C. Larbalestier, Proceedings of the IEEE, 92, No. 10, October 2004, pp. 1639-1654.
- [2] A.P. Malozemoff, S. Fleshler, M. Rupich, C. Thieme, X. Li, W. Zhang, A. Otto, J. Maguire, D. Folts, J. Yuan, H-P. Kraeme, W. Schmidt, M. Wohlfart and H-W. Neumueller, "Progress in high temperature superconductor coated conductors and their applications," Supercond. Sci. and Tech. vol 21, pp. 1-7, 2008.
- [3] A.P. Malozemoff A P, in Proceedings of the 2008 Forum of the World Academy of Ceramics, ed. L. Gauckler, Chianciano Terme, Italy, July 6-8, 2008, to be published
- [4] M.W. Rupich, U. Schoop, D.T. Verebelyi, C.L.H. Thieme, D. Buczek, X. Li, W. Zhang, T. Kodenkandath, Y. Huang, E. Siegal, W. Carter, N. Nguyen, J. Schreiber, M. Prasova, J. Lynch, D. Tucker, R. Harnois, C. King, D. Aized, "The Development of Second Generation HTS Wire at American Superconductor," IEEE Trans. on Applied Superconductivity vol 17, No. 2, pp. 3379-82. 2007.
- [5] A. Goyal, M. P. Paranthaman, and U. Schoop, "The RABiTS approach: Using rolling-assisted biaxially textured substrates for high-performance YBCO superconductors," Materials Research Bulletin, vol. 29, pp. pp. 552-561, 2004.
- [6] M.W. Rupich, D.T. Verebelyi, W. Zhang, T. Kodenkandath and X. Li, "Metal Organic Deposition of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-x</sub> Films for Second Generation High Temperature Superconductor Wires," MRS Bulletin, 29, p. 572, 2004.
- [7] A. Malozemoff, M. Rupich, A. Santamaria, "Scale-up of 2G HTS Wire Manufacturing at American Superconductor," Dept. of Energy High Temperature superconductivity Program Peer Review, Arlington, VA, July 29-13, 2008, Available at: [http://www.energetics.com/supercon08/pdfs/presentations/tuesday/joint/joint\\_2\\_scale\\_up.pdf](http://www.energetics.com/supercon08/pdfs/presentations/tuesday/joint/joint_2_scale_up.pdf).
- [8] C. Cantoni, A. Goyal, E. Specht, X. Li, M. Rupich, "Influence of oxygen deficiency on the out-of-plane tilt of epitaxial Y<sub>2</sub>O<sub>3</sub> films on Ni-5%W tapes," J. Mater. Res., submitted for publication.
- [9] A. Goyal, M. Paranthaman and X. Li, "ORNL-AMSC CRADA: Development of RABiTS-Based 2G Wire," Dept. of Energy High Temperature superconductivity Program Peer Review, Arlington, VA, July 29-13, 2008, Available at: [http://www.energetics.com/supercon07/pdfs/ORNL\\_AMSC\\_CRADA.pdf](http://www.energetics.com/supercon07/pdfs/ORNL_AMSC_CRADA.pdf).
- [10] N. Long, N. Strickland, B. Chapman, N. Ross, J. Xia, X. Li, W. Zhang, T. Kodenkandath, Y. Huang and M. Rupich, "Enhanced in-field critical currents of YBCO second generation (2G) wire by Dy additions," Supercond. Sci. and Tech. vol 18, pp.S405-S408, 2005.
- [11] T. Holesinger, L. Civale, B. Maiorov, M. Feldmann, Y. Coulter, D. Miller, V. Maroni, Z. Chen, D. Larbalestier, R. Feenstra, X. Li, Y. Huang, T. Kodenkandath, W. Zhang, M. Rupich and A. Malozemoff, "Progress in Nano-engineered Microstructures for tunable High-Current, High-Temperature Superconducting Wires," Adv. Materials , vol 20, pp 391-407, 2008.
- [12] E.D. Specht, A. Goyal, J. Li, P.M. Martin, X. Li and M.W. Rupich, "Stacking faults in YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-x</sub>: Measurement using x-ray diffraction and effects on critical current," Appl. Phys. Lett. Vol 91, P52508, 2007.
- [13] Kraemer H-P, Schmidt W, Wohlfart M, Neumueller H-W, Otto A, Verebelyi D, Schoop U and Malozemoff A P 2007 Journal of Physics: Conference Series, to be published
- [14] Seok E Y, Lee C J, Kang H K, Nam K W, Yoon Y S and Ko T K, Paper 1A03, Magnet Technology Conference, Philadelphia PA Aug. 27-30, 2007, to be published
- [15] J.F. Maguire, D. Folts, J. Yuan, D.Lindsay and S. Kurtz, "Development and Demonstration of a Fault Current Limiting HTS Cable at Con Edison Grid," IEEE Trans. on Applied Superconductivity, submitted for publication.