Recent Developments in 2G HTS Coil Technology

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***Abstract*—Recent developments in 2G HTS coil technology are presented highlighting the ability of 2G HTS wire to function under difficult operating conditions without degradation. The challenges of use in various coil constructions and applications are discussed. Several applications where the conductor is subjected to high stress levels include high field insert coils and rotating machinery. While these applications present different challenges, the ability of the conductor to operate under high stress levels has been demonstrated in both direct sample measurement and test coils. The high winding current density that is available with SuperPower's thin 2G HTS wire was utilized in a high field insert coil demonstration generating central fields in excess of 26.8 T [1]. The ability of the wire to be tailored (stabilization, insulation, ac losses) to fit various operating parameters will also be discussed.**

***Index Terms*—High-temperature superconductors, Magnetic field, Stress control, Superconducting coils**

I. INTRODUCTION

SUPERCONDUCTING magnets have been an enabling technology for many advanced applications and opening opportunities for advancements in condensed matter physics, biology, chemistry, material sciences, physiology and psychology [2]-[5]. The development of high magnetic field superconducting magnets has driven many of the developments in magnetic resonance (NMR/MRI), particle accelerators and colliders and fusion devices [6]-[8]. Superconducting magnets offer a number of advantages including smaller footprint (weight, volume) allowing more freedom in the configuration of the rest of the device, and consuming much less power.

The availability of high performance superconducting materials has facilitated the development of high field superconducting magnets. Superconducting magnets are typically made of low temperature superconductors (LTS), principally NbTi and Nb_3Sn. The highest magnetic field generated by a Nb3Sn-based LTS magnet is 22.3 Tesla [2].

With the growing availability of REBaCuO-based second generation high temperature superconductors (2G HTS), revolutionary and novel electric machines and devices, including high field magnets [2], [6]-[8], are now being considered. The high engineering critical current density, high strength and high critical magnetic field of 2G HTS, on the order of 70 Tesla or more, have the potential to breach the limit of today's superconducting magnets using LTS and first generation HTS.

Today, the manufacture of high performance 2G HTS wire is underway The fabrication technologies for 2G HTS materials have been progressing dramatically in the past few years [9]-[12] with remarkable advancements in the metrics of critical current, wire length, in-magnetic-field performance and production throughput and costs..

This paper reports on recent developments in the fabrication of 2G HTS wire and prototype devices at SuperPower Inc., including Zr:GdYBCO based wires with high in-field-critical-currents and related magnet technology developments.

II. 2G HTS WIRE FOR MAGNET APPLICATIONS

The applicability of a superconducting wire for a high field magnet is principally determined by its electrical current-carrying capability and mechanical properties to handle the stresses encountered during fabrication, cooldown and operation. In addition, long lengths of wire are needed for the magnet fabrication.

A. Structure of the SuperPower 2G HTS Wire

Table 1 displays a typical architecture of 2G HTS wire made at SuperPower, Inc.

TABLE 1: TYPICAL ARCHITECTURE OF A SUPERPOWER® 2G HTS WIRE

Architecture	**Process Method**
2x20 μm Surround Cu	Electroplating
2 μm Ag	Sputtering
1~5 μm REBCO HTS	MOCVD
~150 nm Buffer Stack	IBAD / Sputtering
50~100 mm substrate	Electropolishing

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The substrate serves two purposes. It provides the mechanical backbone of the conductor and is the base for growing the subsequent layers. The nickel alloy substrate (typically Hastelloy® C276) is typically either 50 or 100 microns thick. The thin substrate thickness enables a high engineering current density (J_e) in the tape that is critical for magnet applications. It is electrochemically polished (EP) to a surface roughness of less than 2nm and is smooth enough for ion beam assisted deposition (IBAD) of a textured MgO-based buffer stack. The FWHM values of the phi-scan at (110) of the cap layer of the buffer stack typically range from 6 to 8 degrees for the km+ lengths.

Metal organic chemical vapor deposition (MOCVD) is used to grow the REBCO HTS film. The advantages of the MOCVD method include its extremely high deposition rate, ~0.7 μm/min, and ability to extend its deposition area resulting in very high throughput. The REBCO HTS film is then capped by a thin Ag layer to provide good electrical contact. Stabilization of the conductor is provided by an electroplated copper layer that surrounds the entire structure. The thickness of the copper layer can be varied to meet the operational requirements of the conductor in a specific application.

Multiple conductor configurations are available using this process, although the most common standard SuperPower® 2G HTS production wire is called SCS4050 consisting of a 50 micron substrate, ~0.2 micron buffer stack, ~ 1 micron REBCO layer, ~ 2 microns of Ag with 40 microns total thickness of surround copper stabilizer.

B. Current-Carrying Capabilities of 2G HTS Tape

The applicability of a superconducting wire for magnet use is mainly driven by its electrical current-carrying capability under operating conditions. The current-carrying capability of a conductor is characterized by the engineering critical current density as a function of the operating temperature and the magnetic field seen by the windings, $J_e(B, T)$. The high current-carrying capability of SuperPower's 2G HTS wire, combined with its low cross-sectional area results in high J_e values compared to other available wires. For example, for a 4 mm wide wire with a 50 micron substrate and 40 micron total thickness of copper stabilizer, the conductor engineering current density $J_{e\text{-}cond}$ is ~ 2.66 A/mm^2 per amp of operating current. In a coil configuration with a 65% conductor packing factor, this gives a winding engineering current density $J_{e\text{-}wind}$ of ~ 1.73 A/mm^2 per amp of operating current.

The performance of the 2G HTS material in field, including the field orientation with respect to the tape, is of critical importance. Fig. 1 is a plot of I_c vs. field orientation for a variety of tapes with varying REBCO compositions. In this plot, standard production tape composition is represented by the green line.

In a coil application, the performance of the coil is typically dominated by the I_c vs. B performance at field angles from 15 to 30 degrees. With the standard composition, the drop off in I_c is significant in this angle range, often approaching the perpendicular (90 degree) I_c value. However, the magnetic fields in this region of the coil are still relatively high when compared to the peak field in the windings. This combination of high relative magnetic field and depressed I_c pinpoints the region of the coil that is first subject to transitioning from the superconducting state.

Recently, improvements have been made in the Ic vs. magnetic field angle performance of the 2G HTS wire through the replacement of Sm with Gd in the REBCO composition, as well as the inclusion of Zr into the REBCO structure. This has resulted in enhanced pinning and improved Ic vs. magnetic field angle performance, particularly in the critical 15-30 degree range where a factor of 2 improvement has been seen. This improved 2G HTS will greatly enhance the future performance of coils built out of this conductor with advanced pinning.

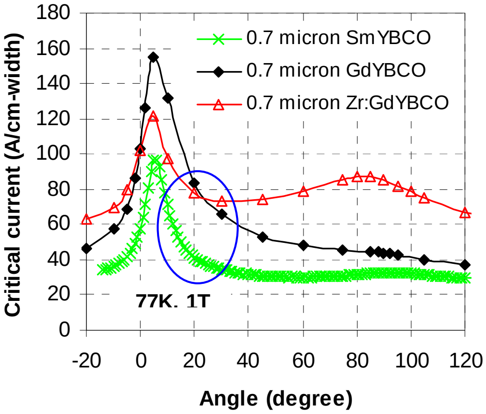

Fig. 1. Critical current as a function of angle between magnetic field and film surface at 77 K, 1 T for 12 mm wide samples with same film thickness but different film compositions. The green line is representative of current standard production tape with Sm doping. The black and red lines are representative of improved conductors with Gd and/or Zr substitution into the REBCO structure. The critical region for coil performance is given in blue.

Splice joints between segments of 2G HTS wire are routinely fabricated using a simple lap joint technology which has recently been automated. The lowest resistance joints are made with the REBCO sides facing each other using a thin intermediate solder layer. For example, 100 mm solder lap joints between two 4 mm wide SCS4050 wires have typical joint resistances on the order of 100-150 nano-ohms.

C. Mechanical Properties of 2G HTS Wire

In order to function properly over the lifetime of the application, the 2G HTS wire must maintain its current-carrying capability under the winding, thermal and magnetic stresses the coil experiences during fabrication and operation. The 2G HTS wire fabricated by SuperPower has the inherent advantage of a built-in structural element with its Hastelloy® C276 substrate, eliminating the need for added external reinforcement. This has the added advantage of keeping the engineering current density high.

Recent axial stress-strain measurements conducted at the Naval Research Laboratory on standard 4 mm wide SCS4050 production wire gave a yield stress for the wire of 970 MPa at 0.92% strain. The high strength of the wire is demonstrated in the I_c vs. stress properties shown in Fig. 2 indicating a stress level of 700 MPa can be sustained in the wire before there is irreversible degradation of the critical current. In addition, axial cyclic loading tests (min/max =0.1) out to 100,000 cycles

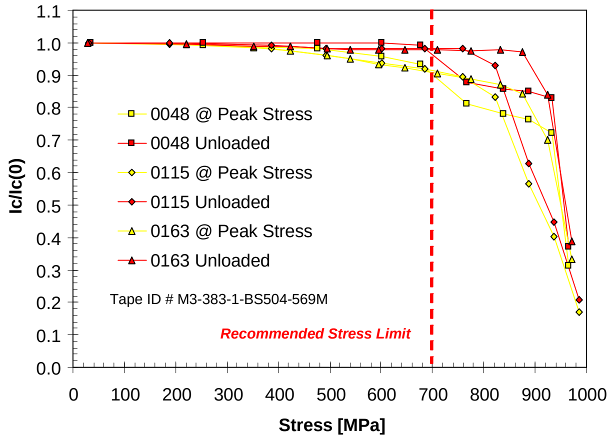

Fig. 2. Plot of normalized critical current (I_c / $I_c(0)$) vs. applied axial stress on a 4 mm wide, standard production SuperPower® 2G HTS wire. A stress limit of 700 MPa is recommended.

were conducted for various stress levels. At levels up to the 700 MPa limit, there was no degradation up to the 100,000 cycles tested (Fig. 3). Above the 700 MPa limit there is gradual degradation of the I_c performance until irreversible damage sets in. This shows that for all practical purposes, the 2G HTS wire has fatigue strength comparable to the irreversibility stress limit of the tape. This high strength is essential considering the high stresses that are often encountered in applications such as high field insert coils or high speed rotating machinery. The advantage of this material for high stress applications is clearly seen in Fig. 4 comparing the operating windows for various LTS and HTS conductors.

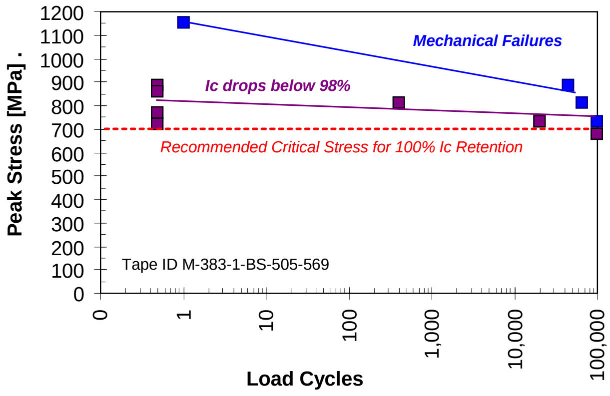

Fig. 3. Plot of peak stress vs. load cycles (min/max = 0.1) on 4 mm wide standard production SuperPower® 2G HTS wire. Below 700 MPa, there is no Ic degradation out to the 100,000 cycle test limit.

Thermal stresses in the coil structure are developed during the cooldown of the coil as well as any thermal transients that may be experienced during fault or quench situations. SuperPower 2G HTS wire has thermal expansion characteristics well suited for inclusion with typical structural materials used in coil construction as shown in Fig. 5.

D. Other Considerations for Using 2G HTS Wire in Coils

For most coil applications, long lengths of wire are required to reduce the number of splices in the coil. Continuous piece lengths of up to 1300 m have been fabricated of the 2G HTS material. Piece lengths of several hundred meters typically show very uniform Ic properties and high n-values of ~30.

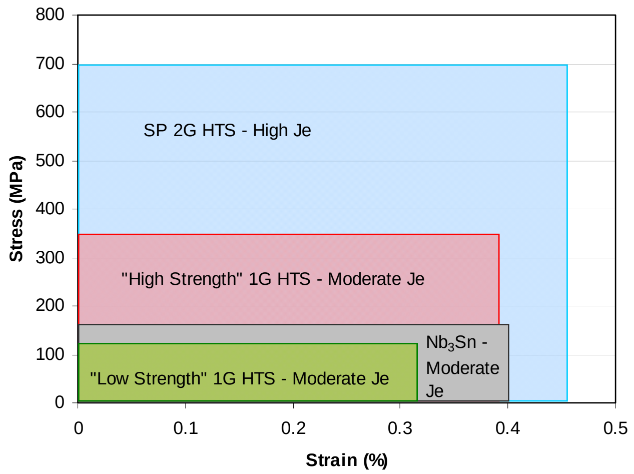

Fig. 4. Comparative operating stress-strain windows for LTS and HTS superconductors. Comparison made at 4.2 K.

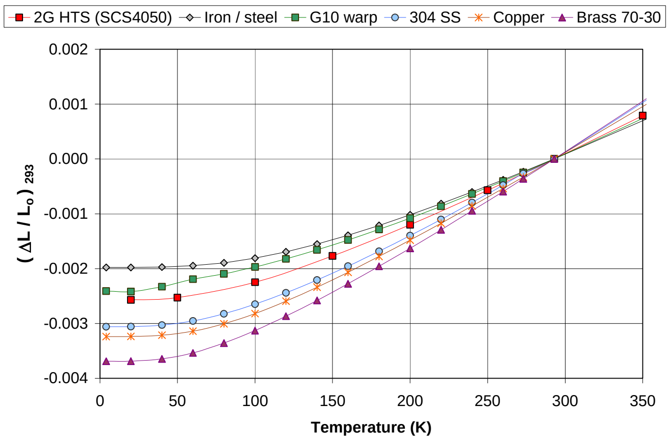

Fig. 5. Thermal expansion of standard production (SCS4050) SuperPower 2G HTS wire compared with other common magnet construction materials.

For applications operating in an AC environment, low AC loss conductor will be required. One technique for addressing the hysteresis AC loss in a conductor is the fabrication of multifilamentary tape with channels cut along the length of the tape to produce the discrete filaments. With these types of structures, the 2G HTS tapes see an AC loss reduction on the order of 5 times or more in the 50 – 100 Hz range. The eddy current loss in the tape is minimized since the Hastelloy® C276 has a very high resistivity of ~ 125 μohm –cm.

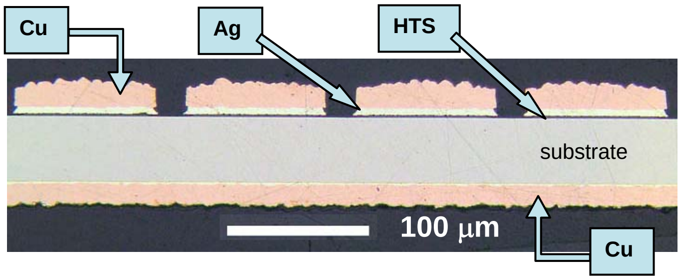

Fig. 6. Cross-section of a SuperPower multifilamentary tape with ~ 100 micron wide filaments and ~ 20 micron wide channels.

III. HIGH FIELD 2G HTS MAGNET TEST

Using ~ 460 m of standard production 4 mm wide SCS4050 wire, we constructed a pancake wound solenoid coil for test as a high field insert coil. The REBCO HTS layer was 1 micron thick and the critical current of the wire used in the coil ranged from 70A to 90A at 77K and self field. The coil was dry wound (without epoxy) using co-wound Kapton® polyimide insulation. The coil used a double pancake construction with copper or silver jumper connections between the individual pancake layers. Some basic construction parameters for the magnet are listed in Table 2. A photo of the magnet is displayed in Fig. 7.

TABLE 2: CONSTRUCTION PARAMETERS OF THE 2G HTS INSERT COIL

Parameter	**Value**
Coil ID	9.5 mm (clear)
Winding ID	19.1 mm
Winding OD	~ 87 mm w/ overbanding
Coil Height	51.6 mm
Number of Pancakes	12 (6x double)
2G Wire Used	462 m total
Number of turns	2772
Coil Winding Je	1.569 A/mm^2 per A of operating current
Coil Constant	44.4 mT / A

At 77K, the coil generated a 0.733 T central field operating at a critical current of 16.5 A with a voltage criterion of 1.0 μV/cm. The magnet was subsequently tested at the National High Magnetic Field Laboratory (NHMFL) at Florida State University in their unique 20 cm wide bore, 20 MW, 20 T Bitter test magnet.

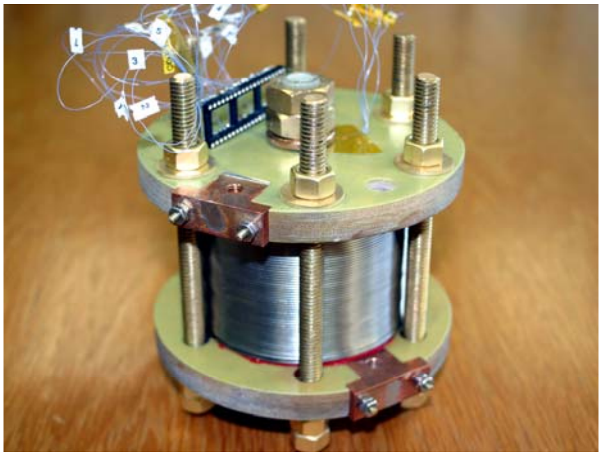

Fig. 7. Photo of high filed insert coil fabricated at SuperPower with standard SCS4050 2G HTS wire. At 4.2 K, the coil generated a self field of 9.8 T and a center field of 26.8 T when placed in a 19 T axial background field. Flange diameter is 127 mm.

At 4.2K, the coil generated a 9.81 Tesla self field operating at a critical current of 221 A. With an axial background field of 19T, the coil generated an additional 7.8 T for a total central field of 26.8 T. Operating parameters of the coil are given in Table 3. Peak operating stress within the coil is estimated to be ~ 215 MPa, well within the strength limitations of the SuperPower standard 2G HTS wire.

TABLE 3: OPERATING PARAMETERS OF THE 2G HTS INSERT COIL

Parameter	**Value**
Avg. I_c (77K, sf) of Tapes in Coil	78 A
Coil I_c (4.2 K, sf)	221 A
Amp-turns @ Coil I_c (4.2K, sf)	612,612 A-turn
Coil Winding Je (4.2K, sf)	346.7 A/mm^2
Peak Radial Field (4.2K, sf)	3.2 T
Peak Central Field (4.2K, sf)	9.81 T
Coil I_c (4.2 K, 19 T axial background)	175 A
Amp-turns @ Coil I_c (4.2K, 19 T axial background)	485,100
Coil Winding Je (4.2K, 19 T axial background)	274.6 A/mm^2
Peak Radial Field (4.2K, 19T axial background)	2.7 T
Peak Central Field (4.2K, 19 T axial background)	26.8 T

IV. SUMMARY

2G HTS wires with high engineering critical current density have been developed and manufactured in long lengths. In field performance of the 2G HTS wires has been remarkably improved through REBCO composition adjustment, high-T_c rare-earth element substitution, Zr-doping and growth condition optimization. The mechanical properties of SuperPower's wire are well suited for high stress coil applications. A coil wound of 2G HTS wire generated 26.8 Tesla magnetic field. We have not reached the limit of 2G HTS capacity. 30 Tesla and beyond is, we believe, within our grasp using the recently improved 2G HTS wires.

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