Development Status of AMSC Amperium® Wire

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Abstract. AMSC produces Second Generation (2G) HTS wire for utility power applications as well as coil, motor and generator solutions. In this paper, various types of AMSC’s Amperium® wire suitable to power cables, fault current limiters and coils are reviewed. In addition, recently developed performance-improvements in amperage, reduced ac power loss and mechanical properties are summarized. The introduction of thicker HTS layers coupled with optimized heat treatments to enhance critical current density dramatically improve both cable and coil wire current-carrying capability. A non-magnetic RABiTS™ substrate has now been developed to the point where it is compatible with the manufacturing process and capable of sustaining large critical currents. Finally, the ability of Amperium® wires to withstand cable-winding stresses, and to exhibit the high transverse c-axis strength critical to the reliability of the wire in coils, are discussed.

1. Introduction
AMSC manufactures and sells high temperature superconductor (HTS) wire for use in high power density transmission cables, fault current limiters (FCL’s), distribution power cables with integrated FCL capability, and light-weight high power motors and generators. AMSC’s wire manufacturing is based on the Rolling Assisted Biaxially Textured Substrate/Metal Organic Deposition (RABiTS/MOD) processes described in detail elsewhere [1,2]. The final wire consists of either 4mm or 10mm HTS ‘insert’, slit from wider strips, laminated between two metal stabilizer strips. The width of the stabilizer is designed wider than the HTS insert so that the regions at the edges are filled with solder (referred to as solder fillets) supplying mechanical strength and hermeticity to the wire.

In this paper, different types of AMSC’s Amperium® wire architectures, and the ongoing development efforts to improve their performance, are described. The paper is arranged in three sections, the first section covers $I_c$ and ac loss for wire used in ac applications operating in low magnetic field at temperatures accessible with liquid nitrogen (LN$_2$), the second section describes $I_c$ of wires designed for coil-based devices operating at low temperature and high field, and the last section highlights the tolerance of the laminated wire architectures to mechanical stresses.

2. Wire for LN$_2$ AC Applications: $I_c$ and AC Loss
Targeted applications that fall into this category include resistive FCL’s and power cables (transmission and distribution). For resistive FCL’s, the wire architectures have been designed with 75μm thick stainless steel (SS) lamina, 12mm in width, around a 10mm HTS insert. Two variants are available: a three layer version with a single HTS insert between the two SS lamina and a four layer option with two (double) HTS inserts and between the lamina [3]. The ability to assemble one or two HTS inserts into a single wire allows for a wide range of wire currents. The typical ranges for the
minimum critical current for the 3-layer and 4-layer wires (with a 0.8 μm HTS layer) are 225-275A and 475-550A, respectively. Figure 1 shows plots of $I_c$ versus position for the 3-layer and 4-layer wire options over representative 500m lengths. The minimum $I_c$’s are 262A and 538A with a standard deviations of 1.3% and <1% for the 3-layer and 4-layer variants, respectively.

Brass cable wire was designed to be robust in cable stranding operations and resistant to buckling under the compressive and bending loads experienced in transmission cables with thick dielectric layers needed for high voltage operation. The wire has a 3-layer composite structure consisting of a 4mm HTS insert laminated between two 4.4mm wide, 150μm thick brass stabilizers. As previously reported, nominal values of the self-field, 77K $I_c$’s ranging from 140-200A have been achieved in brass cable wire by incorporating a 1.2 μm HTS layer optimized for use at LN2 temperatures and low fields [3].

![Figure 1](image1.png)  
**Figure 1.** $I_c$ displayed for each meter of 3-layer and 4-layer SS wires for resistive FCL application.

![Figure 2](image2.png)  
**Figure 2.** $I_c$ map of 50m long brass cable wire with NMS and 1.2μm HTS layer using one meter gauge-length. The minimum $I_c$ is 165A.

![Figure 3](image3.png)  
**Figure 3.** AC loss per cycle vs. peak current for different substrates and HTS thicknesses measured at 50 Hz and temperature ~75K.

In addition to increasing current capacity, development work at AMSC has been focused on reducing the ac loss and magnetic permeability associated with the RABiTS substrate. The Ni5W alloy (atomic percent) presently used in the production wire is slightly ferromagnetic, resulting in a hysteretic energy loss and magnetic susceptibility at low currents (and magnetic fields). The first demonstration of cable wire with a non-magnetic substrate (NMS) using Ni9W RABiTS with good local metrics for texture and $I_c$ on par with the standard wire was reported in reference [3]. Once the feasibility of the NMS technology was established in short lengths with the 0.8μm HTS layer
manufacturing process, 50-70m long strips were produced to verify compatibility with the 1.2μm HTS coating and modified heat treatments designed for higher I_c. Brass cable wire incorporating NMS has achieved I_c ranging from 165A to 176A over 50m as exhibited in Figure 2. The wire with NMS is in the same range as its long-length counterpart with standard Ni5W substrate reported in reference [3].

Figure 3 compares the transport ac loss of a section of NMS cable wire with wires containing 0.8μm and 1.2μm HTS layers on standard Ni5W substrate measured at Los Alamos National Laboratory. The results are as expected, at low currents, the FM contribution dominates the loss of the wire with the standard Ni5W substrate independent of the coating thickness (and I_c) while the loss of the wire with NMS is greatly reduced. At higher currents, the loss is dominated by the HTS contribution and the wires with 1.2μm HTS layer have nearly the same loss regardless of the type of substrate, which is considerably lower than the 0.8μm wire possessing much lower I_c.

3. Wire for Coil Applications: I_c at Low Temperature, High Magnetic Field
Amperium wire designed for coil-based applications is laminated with 50μm thick copper stabilizers and is available in 4.8mm and 12mm widths with 4mm and 10mm HTS inserts, respectively. These wires have wider solder fillets, providing additional strength against delamination when subjected to high transverse c-axis stresses.

Figure 4 shows the I_c versus length for an initial qualification run of a 12mm wide coil wire processed with a 1.2μm HTS layer optimized for coil operating regimes. The minimum I_c for this wire is 385A with a standard deviation less than 1.7% over nearly 575m. Although the 77K, self-field critical current density for coil wire is lower than that for cable wire with the same HTS thickness, its absolute critical current at coil operating conditions (i.e. low temperatures and high fields) is higher. Figure 5 shows a comparison of the critical current in perpendicular field (oriented along the c-axis) at 30K of two wires with 1.2μm HTS layer optimized for the cable or coil operating regimes. The coil wire, optimized for operation at low temperature, outperforms the cable wire by about 20% even though the 77K, self-field I_c of the cable wire is about 20% higher.

4. Key Mechanical Properties: Cable-Winding Tolerance and C-Axis Strength
To date, development and qualification of 4.4mm brass and 12mm copper wires containing the 1.2μm HTS layer have met all existing Amperium wire specifications (see www.amsc.com). Herein one key mechanical test is highlighted for each application.
Sections of 1.2μm HTS-NMS brass cable wire were subjected to a reel-to-reel cable winding test to characterize its integrity in its intended use. The test consists of sequentially going through reverse double bends around six inch rollers, a 360° twist and helical winding around a 19mm diameter former at 10 lb tension. The $I_c$ was measured every one meter before and after the test. The test was carried out twice, once with the wire oriented so that the substrate faced radially inward to the former and once with the substrate oriented radially outward. The results of the cable-winding test, shown in Figure 6, confirm the wire maintains its $I_c$ after repeated tests.

For 12mm copper coil wire, the c-axis strength or transverse delamination strength (breaking strength) was tested since this is an essential property that insures the reliability of the wire in coils, especially when considering stresses endured in epoxy-impregnated coils during cool-down to operating temperature. Figure 7 shows the minimum and maximum c-axis strength at 77K for seven wires with three or four samples taken per wire. The lowest value for this sampling is 40MPa, well-above requirements for in-house coil designs. The distribution in strength reflects variation in centering the HTS insert within the laminated structure. Future improvement in the alignment will raise the minimum values. Naturally more statistics will be assembled as the qualification progresses.

Figure 6. $I_c$ over length is retained after simulated cable-winding test relative to the initial run. Tests were run with substrate oriented both in and out.

Figure 7. Minimum and maximum values of the c-axis strength at 77K for seven 12mm copper wires with 1.2μm HTS layer.

5. Conclusion
Increased performance of Amperium wire with 1.2μm thick HTS layers provides opportunity to reduce the cost of both LN₂ ac applications and low temperature coil applications by requiring less wire to build devices. Enhanced performance in robust brass laminated cable wire has been demonstrated on a non-magnetic RABiTS substrate over moderate lengths which will lower the cost of refrigeration. Initial qualification results for copper laminated over long length show promise of high current with enhanced field performance in a durable wire architecture capable of withstanding large c-axis stresses and resilient to delamination for coil applications.

References

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