Industrial High Temperature Superconductors: Perspectives and Milestones

Lawrence J. Masur, Jürgen Kellers, Feng Li, Steven Fleshler, and Eric R. Podtburg

[1]*Abstract*-- **High Temperature Superconductors (HTS) are widely considered for large power applications used by industrial end-users and electric utilities. The prominent application areas include power transmission cables, electric motors, generators, current limiters, and transformers. The promising design concepts rely on HTS to be a flexible composite conductor, robust enough to handle an industrial environment. Currently, the most advanced manufacturing method for flexible composite conductor is the Bi-2223-OPIT, used by many organizations. Significant advances in HTS technology have been made, with average critical current performance above 115 A at 77 K which is equivalent to an engineering current density of 13.8 kA/cm2. During the past 18 months, American Superconductor increased its HTS wire manufacturing capacity from 250 km to 500 km per year to meet the increased demand for development and demonstrations.**

While this level of quality and quantity enables impressive demonstrations of prototype power applications, it does not fully meet the requirements of commercial economic viability. Therefore, to further decrease wire price to $50/kA-m, American Superconductor is currently siting a new facility dedicated to the manufacturing of Bi-OPIT-2223 wire in quantities of 10,000 km per year. Initial applications for this wire are power transmission cables, industrial motors and electrical generators.

This paper will report on the performance and reliability testing of Bi-2223 tapes. We will discuss the electrical, tensile, compression, and fatigue testing results of tapes manufactured for specific key projects. Also, we will review mass availability of High Temperature Superconductors and we will report on technological and price/performance limitations to be overcome to increase the applicability of HTS in research and industrial devices and equipment.

Index Terms-- **Bi-2223-OPIT, HTS Wire.**

I. Introduction

The presently leading HTS wire technology for practical use is oxide-powder-in-tube deformation-processed wire. It consists of a composite of fine filaments of Bi-2223 in a silver or oxide-dispersion-strengthened silver matrix. Such wire comes in the form of a tape several millimeters wide and a few tenths of a millimeter thick, and is being manufactured by a variety of companies [1]-[5]. Average engineering (full cross-section) current density j_e in greater than 100 m lengths has reached 15,100 A/cm^2 at 77 K and self-field in a wire of dimensions 4.1 x 0.2 mm^2 carrying 130 A. j_e of such wire approximately doubles at 30 K and several Tesla of magnetic field perpendicular to the wire plane. Such performance is adequate for commercial-scale electrical equipment. Mechanical properties are reasonably robust, with critical tensile stress typically 120 MPa in wires of most manufacturers, and 265 MPa in wire reinforced with a thin layer of stainless steel soldered to both sides [6].

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L. J. Masur, F. Li, S. Fleshler, and E. R. Podtburg are with American Superconductor Corporation, Westborough, MA, USA (telephone: +1-508-836-4200, e-mail: LMasur@amsuper.com, FLi@amsuper.com, SFleshler@amsuper.com, EPodtburg@amsuper.com).

J. Kellers is with American Superconductor Europe GmbH, Kaarst, Germany (telephone: +49-2131-64117, e-mail: JKellers@amsuper.com).

II. Electrical Performance of HTS Wire

In a paper of one year ago, Masur et al. [1] report an average, long length performance of 118 A (77K, sf, 1 μV/cm) with a standard deviation of approximately 6% over a population of roughly 29 km of wire. A more recent production run, having a population of roughly 60 km of wire, shows an average performance of 130 A (77K, sf, 1 μV/cm) with a standard deviation of approximately 6%. See Fig. 1 for a comparison of these two Bi-2223 wire populations, illustrating an average performance improvement of 10% over the past year. This graph also provides reason for the selection of a guaranteed minimum performance of 115 A.

As long length Bi-2223 from manufacturing runs continue to improve, so do results from experimental short lengths which have dimensions and process elements consistent with straightforward introduction into the manufacturing process. A recent paper by Huang et al. [7] indicates short length performance results of up to 170 A (77 K, sf, 1 μV/cm) which is an additional 13% improvement over the best long length result of 150 A. This demonstration of high performance Bi-2223 wire gives confidence in the constant and continuous improvement of Bi-2223 for use in near-term applications such as motors, generators, and power cables.

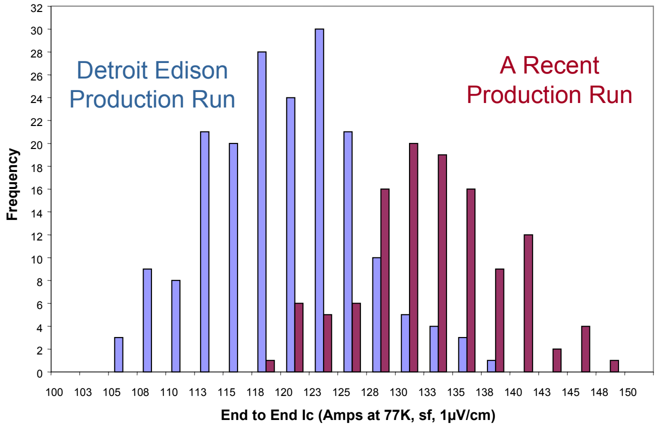

Fig. 1: I_c performance histogram comparing a recent production run to that of approximately one year ago. An increase of approximately 10% is noted in the two population averages (118 A compared to 130 A).

III. Homogeneity and Low Level Defects

For an ideal superconductor, the longitudinal electric field generated by the flow of current follows a power-law,

$$E(j) = E_c \cdot \left(\frac{j}{j_c} \right)^n , \tag{1}$$

where j_c denotes the critical current at which the longitudinal field, *E(j)*, reaches the value of E_c. The standard value for the critical electric field used in the HTS community is $E_c = 10^{-6}$ V/cm. The index value, *n*, is usually determined as the slope in the log *E* vs. log *j* plot.

This definition is certainly useful to mark progress and to compare conductor of different sources, but it can also be misleading. Especially, for large liquid cooled systems and even more so for conduction cooled systems, an operation of the conductor at j_c would lead to often unacceptably large volumetric dissipation rates, $E_c{\cdot}j_c$. For these applications the wire manufacturer needs to qualify its products below E_c at which localized damage to the superconductor becomes apparent. Considering localized defects such as filaments breaks, eqn. (1) needs to be expanded to incorporate an ohmic component,

$$E(j) = E_c \cdot \left(\frac{j}{j_c} \right)^n + \rho \cdot j , \tag{2}$$

which manifests itself as a deviation from the straight line behavior in the double logarithmic plot.

Fig. 2 shows a double logarithmic plot of two wires, both 370 meters long, with similar I_c values at a criterion of 1 μV/cm. However, as is clearly evident in these plots, the wire performance, and thus quality, at electric fields down to 10^{-10} V/cm is quite different. Fig. 3 shows the double logarithmic plot of five long length wires (each 370 meters) in the electric field range of 10^{-5}-10^{-10} V/cm. One can clearly see that Bi-2223 wires can now be manufactured with sufficient quality in long lengths to qualify for demanding applications such as motors, generators and large magnet systems.

Although this Bi-2223-OPIT wire offers very attractive high current densities, many applications require external support of this composite structure. This can be provided using a lamination procedure with stainless steel of which a detailed description can be found in a paper by Masur et al. [6]. This *Bi-2223 High Strength Reinforced Wire* offers the same critical current as the (unlaminated) *Bi-2223 High Current Density Wire,* but at a much higher level of mechanical tolerance, obviously at the expense of a reduced current density.

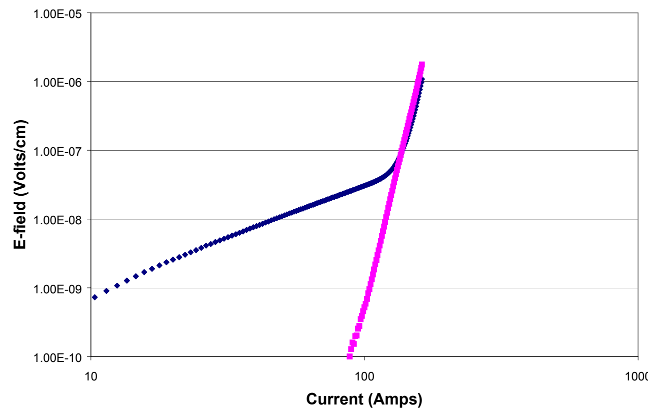

Fig. 2. Double logarithmic *E(j)* curves of two wires, each approximately 370 m long, illustrating a marked difference in performance at electric field conditions that are more sensitive than the standard criterion of 10^{-6} V/cm.

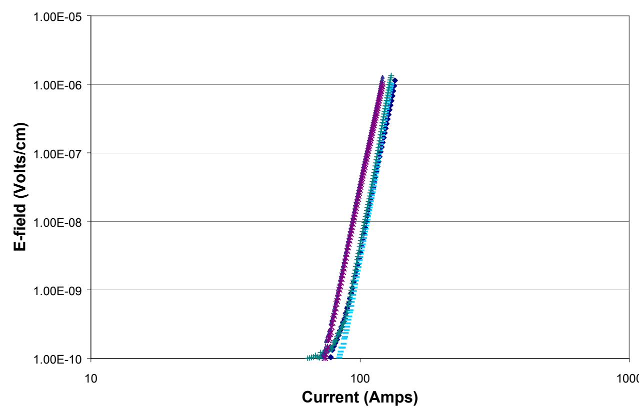

Fig. 3. Double logarithmic *E(j)* curves of five wires, each approximately 370 m long, illustrating consistent and uniform performance over multiple wire runs.

IV. Reliability of HTS Wire

As the critical current performance of BI-2223 wires pass over the threshold required for initial applications, designers begin to look past critical current and additionally focus on aspects of reliability. To this end, statistically-derived data based on large samples populations and high confidence limits become a requirement. As an example of the work being performed at American Superconductor we present one such analysis for the bending properties of our High Strength Reinforced Wire. In this analysis we tested 60 samples to various bend diameters and recorded their I_c degradation.

Using statistical analysis techniques, Fig. 4 displays the minimum bend diameter for a 5% degradation in I_c for both 99.9% confidence (3-sigma) and 99.999% confidence (6-sigma). In Fig. 4, the 6-sigma level has been extrapolated by doubling the 3-sigma interval.

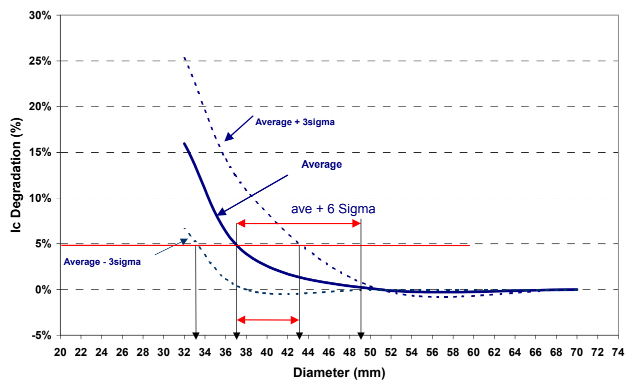

Fig. 4: Results of analysis from 60 test samples investigating degradation in I_c as a function of bending diameter for BI-2223 High Strength Reinforced Wire. Analysis shows minimum bending diameter of 50 mm for 5% I_c degradation at a confidence limit of 99.999% (6-sigma).

Especially for rotating electrical machinery such as motors and generators, designers frequently require fatigue data as they design for long lifetime reliability. The US Naval Research Laboratory, has acquired very encouraging data pointing towards the robustness of these multifilamentary composite structures. In Fig. 5 and Fig. 6 we reproduce results from R. Holtz **[8]**. In Fig. 5 we show the results of tensile fatigue along the longitudinal axis of the wire, and in Fig. 6 we show the results of tensile fatigue in the direction transverse (c-direction) to the face of the wire. In both cases the data indicate that the critical current remains stable out to 100,000 cycles or more when the applied stress is maintained below a critical threshold value.

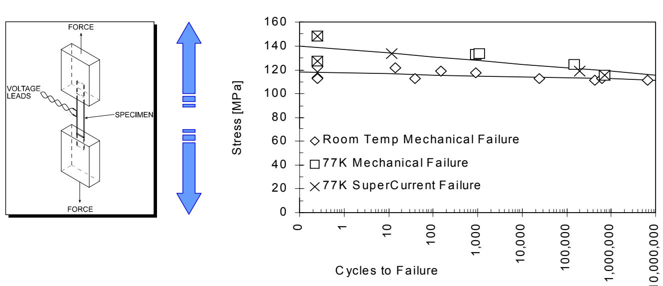

Fig. 5: Results of uni-axial tensile fatigue test on non-reinforced Bi-2223 wire. The data indicate that at stress levels less than approximately 100 MPa there is no degradation in critical current after 1 million cycles.

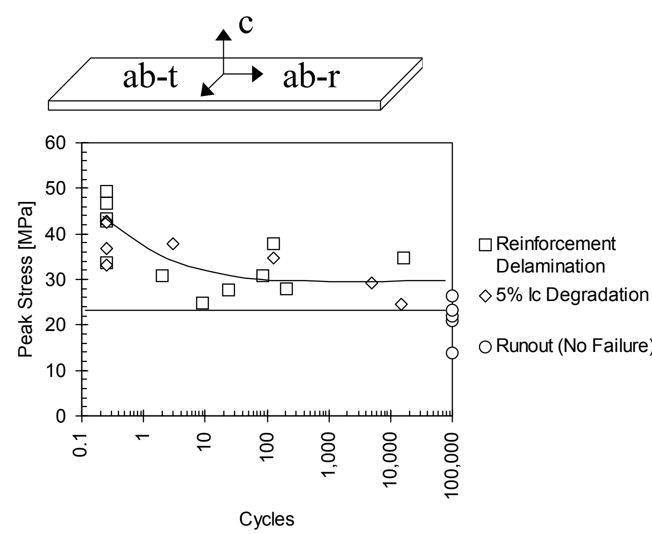

Fig 6a and 6b: a) Schematic showing direction of c-axis tensile fatigue test. b) Results of tensile fatigue test on high strength reinforced Bi-2223 wire. The data indicate that at stress levels less than approximately 24 MPa there is no degradation in critical current after 100,000 cycles.

As a further reliability aspect, Pirelli Cables and Systems together with and American Superconductor have developed tests that simulate the operating environment of the Bi-2223 wires in a cable application. Some of these tests illustrated the shortcomings of early generations of Bi-2223 wires and resulted in considerable development activities. For example, one discovery made last year is the importance of testing Bi-2223 wires during long term exposure to liquid nitrogen. Bi-2223 wires, when exposed to liquid cryogen for long periods of time, can allow for liquid cryogen penetration into the HTS filaments through microscopic defects in the outer sheath of the wire. If this occurs, then a large volume expansion within the HTS filament will result during de-pressurization and warming of the HTS cable system. The result of such an event is considerable degradation of the critical current of the Bi-2223 wire, with obvious impact to the performance of the cable system.

American Superconductor and Pirelli have jointly developed a processing technique for ensuring that Bi-2223 wires for use in cable applications are completely impermeable to liquid cryogen. In addition, we have also jointly developed a proof testing procedure to ensure that every wire used in a cable application meets the stringent requirements for a cable system. These requirements include (1) physical dimensions, (2) critical current, and (3) resistance to liquid cryogen penetration.

To anticipate flaws that may be generated during conductor stranding, a new mechanical aging test intended to simulate the mechanical forces that occur during the conductor stranding operation has been implemented. This test, shown schematically in Fig. 7, simulates the bending, twisting, and tensile forces experienced by the HTS wires during conductor stranding. This test, which is a continuous test from pay-off to take-up, is run on 30 to 50-meter samples of wire cut from the ends of the wires delivered to Pirelli.

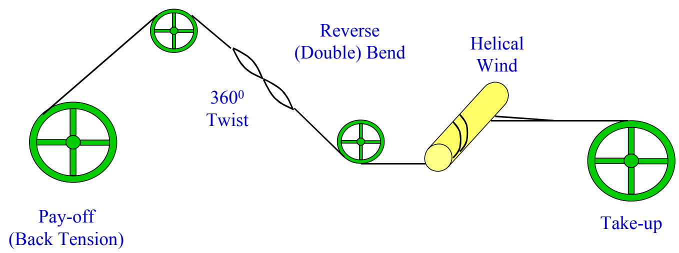

Fig. 7: Schematic of new mechanical aging test designed to simulate the conductor stranding process.

The mechanical aging test illustrated in Fig. 7 is designed to accelerate the formation of flaws due to the stranding operation, however this test does not address the formation of imperfections that might result from the thermal excursions experienced by the Bi-2223 wires during the cable lifetime. To anticipate these thermally-induced flaws, two additional tests were developed and inserted into the reliability testing protocol. One test, referred to as thermal aging, exposes the wires to an elevated temperature for an extended period of time to simulate the curing and baking process used by Pirelli in applying the extruded dielectric and conditioning the cryostat. The other test, thermal cycling, exposes the wires to 10 thermal cycles from room temperature to 77 K. These two tests, plus the mechanical aging test, have been combined into a suite of tests that we refer to as reliability testing and is illustrated schematically in Fig. 8.

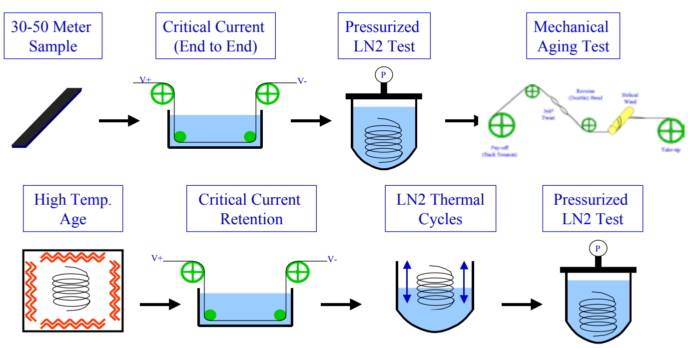

Fig. 8: Schematic of new reliability testing procedure for all BI-2223 wires for use in the Detroit Edison project.

Over 150 Bi-2223 wire samples were processed through the test shown in Fig. 8 to ensure that the wires would be robust and reliable enough for this cable project. Of the over 150 wire samples tested, only one showed an unacceptable degradation in critical current, and none showed penetration of liquid cryogen into the HTS filaments.

The reliability tests developed by American Superconductor and Pirelli for the Detroit Edison project are the most severe and demanding tests used to date for qualifying HTS wires. However, the long term reliability requirements of other HTS applications such as motors can be different, and the reliability testing procedures will be adopted to the specifics of these applications.

V. ECONOMICS OF BI-2223-OPIT WIRE

As HTS technology has matured beyond the levels of feasibility demonstrations, aspects pertaining to commercial viability become essential. Lowest cost, highest performance is the simple key to commercialization of HTS wire. The actions to which this paradigm translates are (a) increase manufacturing capacity to ensure unremitting availability to end customers, (b) reduce the manufacturing cost to commercialize broader markets, (c) improve process consistency by moving to a fully stabilized industrial manufacturing mode.

These actions are addressed simultaneously by a new large-scale manufacturing facility which American Superconductor has begun to construct in August 2000 in Devens; USA. This 33,000 m^2 manufacturing plant (Fig. 7) is dedicated solely to the production of Bi-2223-OPIT, and will make use of many opportunities for reducing labor costs, such as the use of larger billets, process automation, longer strand lengths, multi-die machines, faster line speeds and combining certain process steps.

Fig. 9: Manufacturing floor of American Superconductor's new manufacturing facility having an initial capacity of 10,000 km/a.

The plant will have an annual manufacturing capacity of 10,000 km, scalable to twice that amount as demand grows. This facility will enable a price/performance ratio of \$50/kA-m by 2004. Today, Bi-2223 wires sell for approximately \$200/(kAm) in moderate quantities, and just one year ago they sold for \$300/(kAm). The historical cost/performance curve, with projections to 2004, is shown in Fig. 10. At the price of \$50/(kAm), certain classes of motors, generators, and power cables become economically viable.

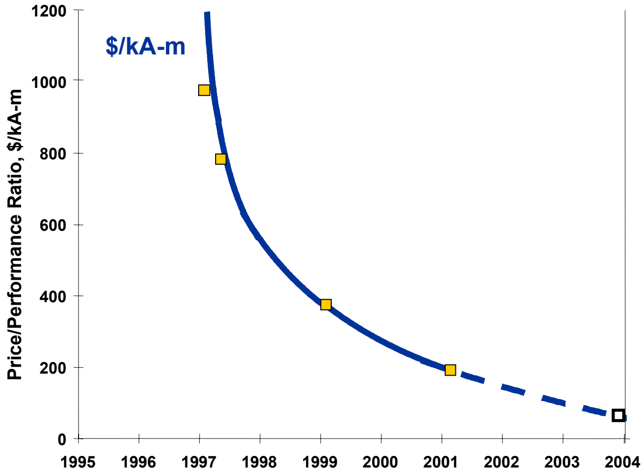

Fig. 10. Historical data and future projections for the Price/Performance ratio of Bi-2223 wires in large production quantities such as those to be manufactured from the new Devens, USA, factory.

VI. Summary

Bi-2223-OPIT technology has made huge strides towards commercialization. The levels of electrical performance meet or even exceed the requirements for beta-site operating systems. Long term reliability testing and a complete engineering database is in progress, and examples have been [9] given in the paper. The next leap towards high-yield, low-cost manufacture is expected with the full operation of the new large-scale manufacturing plant in Devens, Massachusetts, USA.

VII. References

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