DEVELOPMENT OF PRACTICAL HIGH TEMPERATURE SUPERCONDUCTING WIRE FOR ELECTRIC POWER APPLICATIONS

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Abstract

The technology of high temperature superconductivity has gone from beyond mere scientific curiosity into the manufacturing environment. Single lengths of multifilamentary wire are now produced that are over 200 meters long and that carry over 13 amperes at 77 K. Short-sample critical current densities approach 5 x 10^4 A/cm^2 at 77 K. Conductor requirements such as high critical current density in a magnetic field, strain-tolerant sheathing materials, and other engineering properties are addressed. A new process for fabricating round BSCCO-2212 wire has produced wires with critical current densities as high as 165,000 A/cm^2 at 4.2 K and 53,000 A/cm^2 at 40 K. This process eliminates the costly, multiple pressing and rolling steps that are commonly used to develop texture in the wires. New multifilamentary wires with strengthened sheathing materials have shown improved yield strengths up to a factor of five better than those made with pure silver. Many electric power devices require the wire to be formed into coils for production of strong magnetic fields. Requirements for coils and magnets for electric power applications are described.

Introduction

Since the discovery of the rare-earth-doped oxide, or high temperature, superconductors, private companies have been developing wires and cables for energy-related applications.[1] Wires under development contain bismuth-based

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2212 and 2223 phase materials and the new thallium powder. The largest market for low critical temperature wire continues to be for medical imaging and high energy physics experiments. However, new markets are developing for high temperature superconducting wires due to reduced refrigeration and capital equipment costs associated with operating electric power equipment at temperatures above 20 K (see Fig. 1).

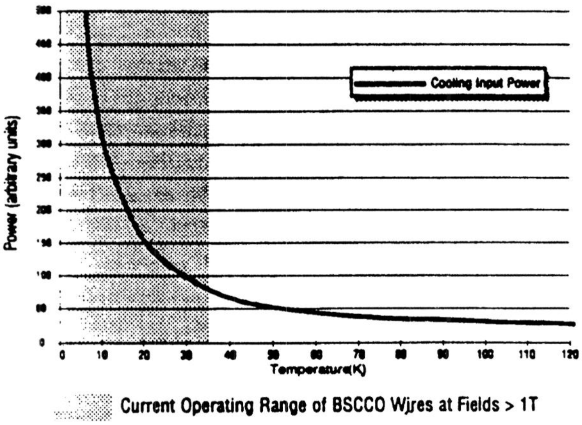

Fig. 1. Refrigeration power requirements vs operating temperature.

Private companies have now developed oxide superconducting powder processes and wire fabricated from the powders as well as prototype components for electric power applications. Such applications include electric motors and generators, transmission lines, fault current limiters, and current limiting reactors and inductors.

Superconducting Wire Development

Silver-sheathed wires are made using a powder-in-tube technique.[2]

Powders are placed into hollow cylinders of silver or silver alloys, sealed, and then processed using a powder-specific series of heat treatments and deformation steps to yield the final, superconducting phase assemblage as well as the desired final form of the wire. Wires may be produced in either flat "ribbon," or tape form (the same final shape used to produce some low-temperature Nb_3Sn wire) or left in a conventional round shape. An optical photomicrograph of the cross section of a 37-filament, 215-m-long tape is shown in Fig. 2.

This wire carries 13 amps at 77 K and has a core critical current density (J_c) of 10,000 A/cm^2. A monofilament wire of the same phase assemblage carried 20 amps at 77 K. As shown in Fig. 3, there is presently more controlled uniformity in critical current over the wire length with the multifilamentary wires. In addition, short (<1 m) lengths of prototype wires now routinely carry nearly 50,000 A/cm^2 at 77 K. The BSCCO-2223 phase, however, will have limitations for high-field applications at liquid nitrogen temperatures due to flux motion. This limitation can become severe for flat tapes used in large coils where there may be a large component of the magnetic field in the direction perpendicular to the plane of the tape. Because of these anisotropy effects, and because the round conductors may offer advantages for use with ac current, several companies are exploring the use of round, multifilamentary BSCCO-2212 superconductors for applications below 40 K.

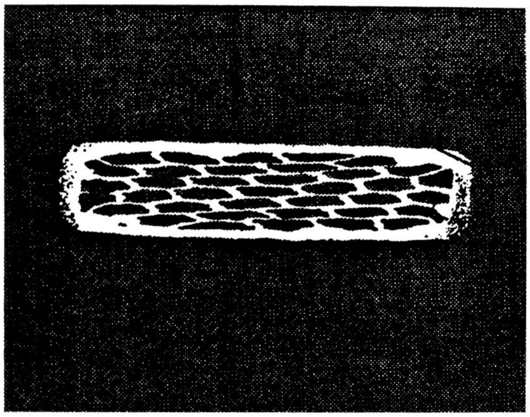

Fig. 2. Optical photomicrograph of mulitfilament BSCCO-2223 wire after heat treatment. There are 37 filaments of 45-µm thickness.

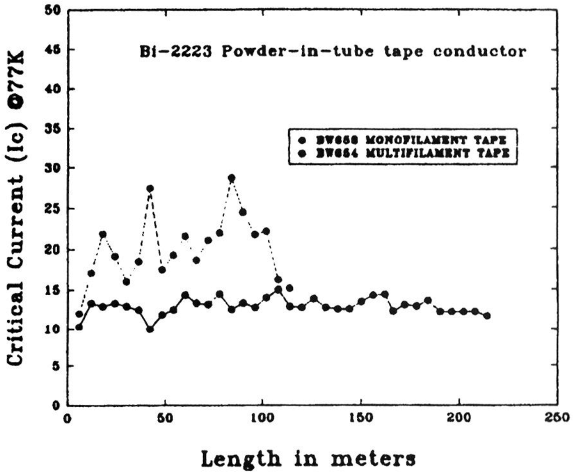

Fig. 3. Variation in critical current density over length for multifilamentary (solid line) and monofilamentary (dashed line) wires.

Round wires show promise

Marketability of the wire, a key concern for any wire manufacturer, can be enhanced by reducing manufacturing steps and by improving material properties over long lengths. Short twist pitch lengths are desirable to enable low-loss operation in the presence of ac current or time-varying magnetic fields as may be present in rotating machinery. Round, multifilament wire processed by the powder-in-tube process is inherently well-suited to the manufacture of long cable lengths. In this case, the superconducting properties are developed through a melt process rather than a roll and sinter operation typical of flat tapes. Fig. 4 shows the microstructure of a 259-filament BSCCO-2212 round wire that carries 165,000 A/cm^2 at 4.2 K. The J_c increases with decreasing filament diameter, with the highest J_c occuring in round wires with 11-µm-size filaments.[3] A summary of typical critical current densities in powder-in-tube wires is shown in Fig. 5.

The Energy Applications

National laboratories have teamed with U. S. industry to enable development of energy applications for the high temperature superconducting wire. Some teaming arrangements take the form of cooperative agreements, which involve no exchange of funding but provide private companies the unique facilities and skilled scientists and engineers necessary for wire development. The national laboratories have active research and development activities under way in most of the energy applications of superconductors, and these partnerships support the goals of each organization.

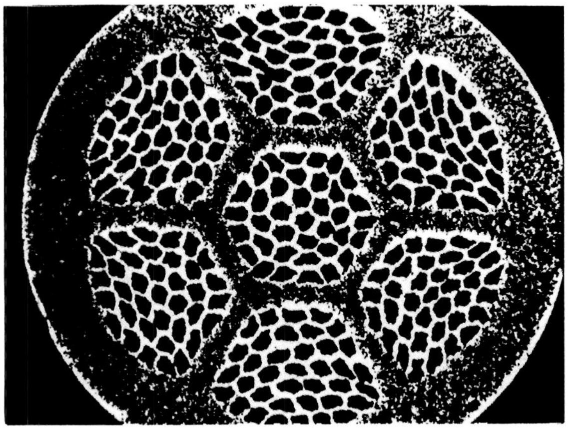

Fig. 4. Optical photomicrograph of 259-filament BSCCO-2212 round wire (before heat treating) with 16-µm average filament width. Wire diameter is 0.05 cm.

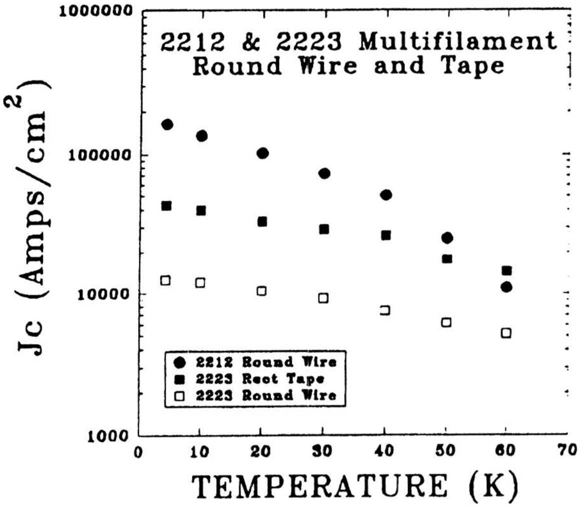

Fig. 5. Critical current density as a function of operating temperature for round and tape-form multifilamentary conductors.

High temperature superconductors are being developed for applications such as fault current limiters[4], current downleads,[5] magnetic bearings for energy storage systems,[6-8] motors,[9,10] and generators.[11] Application of the wires has also been suggested for inductors for switching power supplies[12] and for transformers.[13] At least one group has developed a motor/generator concept with stationary superconducting magnets[14] to simplify the cooling system. A good overview of the potential applications of high temperature superconductors in the power area may be found in several of the references.[1, 15]

Wire and Magnet Performance Requirements

Wires must be capable of enduring bending strains of at least 0.2% for most energy applications. One means to increase the strain tolerance of wires and tapes is to strengthen the silver sheath. This sheath becomes work-hardened after the deformations and heat treatments required to produce the wire. A promising technique for strain enhancement is to add aluminum oxide (Al_2O_3) to the silver. As shown in Fig. 6, such dispersion-hardened sheathing can increase the yield strength of the wires by a factor of five.

Coils and magnets must have high overall winding critical current densities, acceptable strain, electrical, and thermal properties, and low joint resistance between lengths of wire.[16] The losses must be minimized in the presence of ac

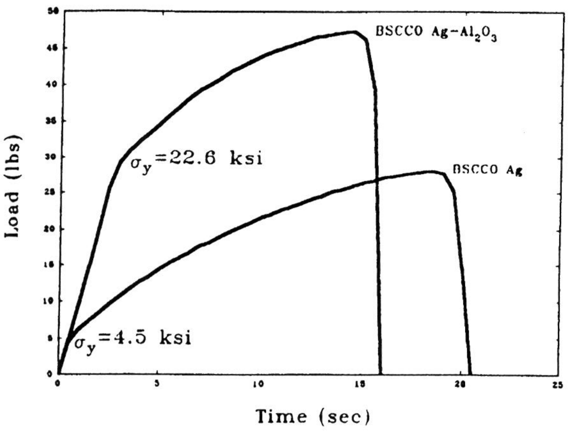

Fig. 6. Effect of Al_2O_3 addition to silver sheath for powder-in-tube wires.

currents or other sources of time-varying magnetic fields, and detection and magnet protection systems must be provided for in the event of a quench. Although quench propagation velocities are expected to be low, normal zone voltages will be adequate to allow detection of normal zones before the conductor overheats.[17]

While early magnets were fabricated using a "wind-and-react" technique,[2] most recent magnets are now made with pre-reacted wire. These magnets required the developmentof efficient react-and-wind fabrication approaches, with low-temperature insulation and epoxy impregnation techniques to maintain the wire's superconducting properties. Record performance for a high temperature superconducting magnet was achieved using a stack of ten pancake coils and three co-wound tapes per pancake (Fig. 7). In a 1-in. bore, the coil produced a field of 2.6 T at 4.2 K and 1.8 T at the relatively warm temperature of boiling neon (27 K).[18] This magnet also produced a record 1.0 T at 4.2 K with a 20-T background field.

Cost Targets

Estimates for the desired cost of the high temperature superconducting wire vary depending on the application and the expected life-cycle costs of the equipment compared to traditional, non-superconducting, or low temperature superconducting versions of that same equipment. For the rotating machinery applications, wire manufacturers have suggested cost targets in the $5-10/kA-m range. Power applications in which the superconductor remains stationary, such as fault current limiters or transmission cables, may command a premium of 2-10 times this cost. By comparison, NbTi wire may be purchased for as little as $1.50/kA-m, depending on the wire specifications, and Nb_3Sn tape is typically $4-8/kA-m, again depending on wire performance.

Early commercialization expected

Some of the earliest commercial prototypes for high temperature superconductors will come from power applications that have less stringent field requirements compared to the large rotating machines. These applications, which include

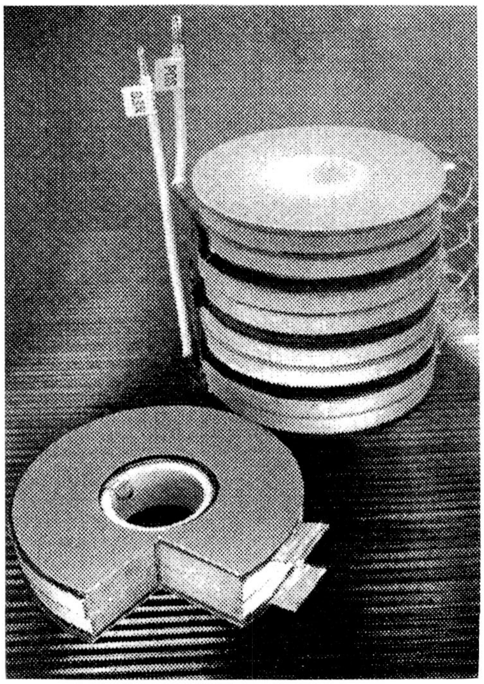

Fig. 7. Prototype high temperature superconducting magnet showing construction similar to world-record 2.6-T magnet (4.2 K). Coil consists of a four-high stack of double pancake modules.

fault current limiters, inductors and transformers, and transmission lines will see full commercial service within the next 5-8 years with continued progress in wire development.

The energy applications that require strong magnetic fields, such as motors and generators, also continue to be developed in the United States and abroad. The U. S. Department of Energy's Superconductivity Partnership Initiative is providing cost-shared contracts to three industry teams. The teams will develop a 100-hp prototype motor, the design and coils for a 100-MVA generator, and a prototype fault current limiter. Electric utility participation on the teams will assure a customer focus on the part of the systems developers and the national laboratories. Development of full commercial products is expected to occur during the next 7-9 years.

Summary

A summary of the wire performance requirements for four different energy applications of high temperature superconductors is shown in Table 1.[19] Wire is being developed with the requisite current-carrying performance at intermediate temperatures to enable early prototype equipment to be designed and fabricated. Cost and manufacturing issues are being addressed by producing round wires with superior electrical transport properties and with great potential for use in ac current and field applications. Strengthened sheathing has been developed to improve the strain tolerance of the wires. Numerous new markets are expected to develop in the electric equipment industry as a result of the development of high temperature superconducting wires.

Table 1. Performance requirements for high temperature superconducting wire

Electric power application	J_c (A/cm^2)	Field (T)	T_{op} (K)	I_c (A)	Wire length (m)	Strain (%)	Bend radius (m)
Fault-current limiter	10^4-10^5	1-3	20-77	10^3-10^4	100	0.2	0.1
Large motor (1000 hp)	10^5	4-5	20-77	500	1000	0.2-0.3	0.05
Generator (100 MVA)	5×10^4	5	20-50	1000	2000	0.2	0.1
Transmission cable	10^4-10^5	<0.2	77	25-30[a]	100	0.4	2
[a]Current in individual wire. Cable will have 100 or more parallel wires.							

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