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Review of Activities in USA on HTS Materials

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ABSTRACT

Rapid progress in attaining practical applications of High Temperature Superconductors(HTS) has been made since the discovery of these new materials. Many critical parameters influencing HTS powder synthesis and wire processing have been identified through a combination of fundamental exploration and applied research. The complexity of these novel materials with regard to phase behavior and physical properties has become evident as a result of these careful studies. Achieving optimal mechanical and superconducting properties in wires and tapes will require further understanding and synergy among several different technical disciplines. Highlights of efforts towards producing practical superconductors for electric power applications based on rare earth-, bismuth-, and thallium-based systems are reviewed.

KEYWORDS: Superconductor, review, wire development, power applications

INTRODUCTION

High Temperature Superconductors(HTS) will be useful in numerous applications advancing both electric power efficiency and electronic device capabilities. Substantial commitments of personnel and facilities to HTS development by numerous organizations throughout the world are testimony to the significant technological potential of this area. Tremendous progress has been made in the manufacture of practical HTS wires, bulk forms, and thin films. Concurrent processing studies are underway to overcome the remaining technical barriers. HTS wires are now being successfully processed with critical currents and lengths appropriate for many commercial uses. Components utilizing these HTS tapes are being manufactured for incorporation in fault current limiters, motors, generators, and power transmission lines. Progress associated with HTS wire development within the United States is reviewed in this report.

EXPERIMENTAL APPROACHES

A large variety of techniques and disciplines have been employed in the developing HTS materials. Much of the progress in processing of HTS wires can be attributed to understanding phase development occurring during the powder synthesis and wire heat treatment stages. Relationships of HTS phase behavior to superconducting properties are significantly more complex than initially envisioned. This uncertainty is due in part to the metastable nature of the HTS phases at room temperature. Further applied materials studies are still needed to optimize HTS properties.

Critical current levels of HTS wires are directly related to the quality of the superconducting powders used in the processing. Most of the early HTS powder synthesis efforts were conducted by multiple sintering and grinding of oxide/carbonate mixtures to produce only a few grams. These laboratory scale studies

have now been extended to large batch processing often involving solution precipitation or aerosol spraying. High quality HTS powders that are fully reacted or partially sintered are available in kilogram quantities from a variety of commercial sources. An average grain size of less than 2 microns and a carbon content of less than 200 ppm are desirable qualities. In the case of Bi2223 wire development, precursor mixtures produce[1] the highest critical current densities.

Processing of HTS wires into long lengths with appropriate properties for commercial applications requires innovative and careful studies by a variety of techniques. Most wire development efforts have involved the oxide-powder-in-tube(OPIT) process which is based on drawing and rolling of HTS-silver tubes. This technique yields composite tapes that are subsequently subjected to a series of sintering/deformation steps to obtain the desired superconducting properties. The tape configuration is advantageous in that the HTS core is protected from atmospheric and mechanical degradation. The OPIT process has been adapted to obtain multifilamentary structures that enable thinner HTS core thicknesses with increased flexibility. Superconducting tapes containing Bi2223, Bi2212, or Tl-1223 phases have yielded promising J_c values over relatively wide ranges of temperature and magnetic fields. Processing of Bi2223 wires proceeds on the basis of solid state sintering with limited liquid formation. Initial Bi2223 powders involve precursor mixtures based on Bi2212 combined with solid solution phases such as $(Ca,Sr)_2PbO_4$, $(Ca,Sr)_2CuO_3$, $(Ca,Sr)CuO_2$, and $(Sr,Ca)_{14}Cu_{24}O_x$. Bi2223 formation during wire sintering processing is the result of a complex set of reactions possibly involving the silver sheath in promoting texture development at the interface with the superconducting core. To achieve the highest critical current densities requires multiple processing steps of mechanical deformation and heat treatments to achieve the highest critical current densities. Processing of Bi2212 tapes involves a single step process entailing peritectic dissociation and reformation of the HTS phase within the core; however, application appears limited to temperatures below about 30 K. A promising alternative method involving sintering of silver wires externally coated with Bi2212 or Bi2223 has also yielded promising critical current values in relatively long lengths. This technique has the advantages of ease of processing and characterization, although is more susceptible to degradation.

Development of Tl-1223 wires has progressed using the OPIT method with solid state sintering to densify the superconductor and interconnect the grains. It is probable that liquid formation occurs during the processing of the Tl-1223 wires; however, due to faster reaction rates, sintering proceeds to completion within hours rather than weeks. It has not been possible to achieve significant texturing of the Tl-1223 within the OPIT processing, although relatively few attempts have been made due to the hazardous nature of the thallium. Thick films of Tl-1223 deposited on flexible substrates have shown significant texturing indicating the potential of this superconducting phase to yield high critical current densities at liquid nitrogen temperature and in a high magnetic field.

Another approach entailing ion assisted sputtering of a buffer layer on nickel followed by laser ablation of Y123 has been successfully employed to achieve very high critical current densities over laboratory lengths(1 cm). Extension of this method to produce longer lengths in a continuous process is now being conducted.

The usefulness of an HTS phase depends upon a particular application. It is obvious that Bi2212 wires could be useful for operations at 4-25 K in higher magnetic fields up to 20 T and beyond. Another potential near term use entails superconducting current leads operating between 4-77K. Due to the very low thermal conductivity of the Bi2212 phase, busbars processed from this phase could carry significant currents with

minimal heating effects in applications ranging from MRI through SMES. Bi2223 wires are being applied in superconducting power transmission lines cooled by liquid nitrogen because of the relatively low associated magnetic fields(<0.2T). TI-1223 wires could be useful for a variety of applications at 77 K and high magnetic fields if barriers of weak links and lower Jc values can be overcome.

RESULTS AND DISCUSSION

Researchers are rapidly achieving very promising superconducting properties from the processing of HTS wires. Technical barriers remain to be overcome prior to full implementation of these materials; however, production of viable HTS magnets, current leads, and cables can be expected within the next two years. HTS wire development has recently been advancing towards processing of longer lengths that exhibit significantly higher critical current densities. Representative critical current densities are summarized in Table 1 for various HTS wires developed within the United States.

Table 1. Representative Critical Current Densities(1 microvolt/cm criteria) for HTS Wires Processed in the United States

Source	HTS	Jc(77K) (A/cm ²)	Length (m)	Description
Riley[2]	Bi2223	16,500	64	
		15,200	280	
		9,100	650	
Balachandran[3]	Bi2223	45,000	0.01	Pressed
		29,000	0.01	Rolled
		15,000	70	
Marken[5]	Bi2212	910,000*	0.04	Dip Coat(4 microns)
		100,000*	0.04	(10 T)
Ren[9]	TI-1223	21,000	20	
Wu [10]	Y123	800,000	0.01	IBAD/Ni(1.4 microns)
*Jc(4K)				

Much of the industrial effort into HTS wire development is associated with OPIT tape processing;. Riley and coworkers[2] at American Superconductor recently obtained a Jc(77K) of 9100 A/cm² using a 1 microvolt/cm criteria over a 650 meter length of Bi2223 tape with progressively higher values over shorter lengths. Balachandran and coworkers[3] reported a corresponding value of 15,000 A/cm² over a 70 meter length of Bi2223 tape produced at Intermagnetics General. These workers also obtained impressive 45,000 and 29,000 A/cm² for pressed and rolled short tapes, respectively. Corresponding BSCCO tapes were used[4] to manufacture a magnet generating 2.6T at 4.2K. Generally critical current densities for Bi2212 wires are superior to corresponding Bi2223 values below about 25 K. A good example of this effect is the work by Marken et al[5] at Oxford Instruments where Bi2212 was dip coated onto silver tapes. These films(4 microns thick) displayed Jc(4K) values of 910,000 and 100,000 A/cm² at self field and 10 T, respectively.

To achieve the high Jc(77 K) values in high magnetic fields requires good magnetic flux pinning. The Jc(77K) values for BSCCO tapes are relatively high at self field; however, rapidly decrease when subjected to a magnetic field due to inherently poor magnetic flux pinning. Recent studies by Krusin-Elbaum et al[6] using proton bombardment to cause Bi fissioning introduced splayed columnar defects that increased the irreversibility line of Bi2212 from 35 K to over 60 K. This procedure could be an enabling technology for HTS applications at higher temperatures and magnetic fields.

Another approach to achieving higher values of $J_c(77\text{ K}, 2\text{ T})$ in HTS wires involves use[7] of thallium based superconductors such as the $\text{TlBa}_2\text{Ca}_2\text{Cu}_3\text{O}_9$ (Tl1223) phase. Normally a fraction of Tl is substituted with Pb or Bi concurrently with replacement of a fraction of the Ba content with Sr. Examples would be use of $(\text{Tl}_{0.8}\text{Bi}_{0.2})(\text{Sr}_{1.6}\text{Ba}_{0.4})\text{Ca}_2\text{Cu}_3\text{O}_x$ or $(\text{Tl}_{0.8}\text{Bi}_{0.2})(\text{Sr}_{1.6}\text{Ba}_{0.4})\text{Ca}_2\text{Cu}_3\text{O}_x$ compositions. Substitutions of the Tl and Ba appear to enhance formation of the Tl-1223 phase with commensurate improvement of the superconducting properties such as T_c and $J_c(77\text{ K})$. The nature of the Tl-1223 phase has been shown to be superior flux pinner to the BSCCO phases although it is more difficult to process into a textured wire. DeLuca[8] using spray pyrolyzed Tl-1223 thick films deposited on YSZ substrates have obtained high transport $J_c(77\text{ K})$ greater than $100,000\text{ A/cm}^2$ with an order in magnitude decrease at a magnetic field of 1T. Ren and Wang[9] obtained a $J_c(77\text{ K})$ of $21,000\text{ A/cm}^2$ over a 20 m length of Tl-1223 wire manufactured by the OPIT process and cooled at 77 K. Further work is required in reproducibly achieving longer Tl-1223 wire lengths with improved J_c values at higher temperatures and magnetic fields above 2 T.

An alternative wire process entails use of Y123 thick films deposited by Wu et al[10] on a nickel alloy(Hastelloy) using buffer layers produced by an ion assisted deposition technique. The resulting values of $J_c(77\text{ K})$ are as high as $800,000\text{ A/cm}^2$ with an associated $I_c(77\text{ K})$ value greater than 70 A for a 2 micron thick film. This approach offers an alternative to the powder-in-tube approach for achieving high current carrying ability in a long wire at 77 K and above 2 T.

Any commercially viable process must be based on an economical approach that has high reproducibility and manufacturing ease. Development of HTS materials has been rapidly progressing towards practical applications. Potential benefits to mankind of this new technology will not only enhance the efficiency and reliability of electric energy usage, but will open internationally new commercial markets in advanced HTS applications enhancing lives of future generations.

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