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REVIEW OF SUPERCONDUCTORS FOR HFM

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Abstract:

A general review of commercial composite superconductors for application in high-field accelerator magnets is presented.

1. GENERAL REQUIREMENTS FOR STRANDS

The overall $\mathbf{J_c}$, the effective filament diameter **d**, and the **strain sensitivity** are related to the intrinsic nature of the SC, while the **processing method**, the piece **length**, and the **cost** are related to fabrication and processing. These are non-independent criteria, since the manufacturing process influences both cost and properties, and so far increases in $\mathbf{J_c}$ have resulted in an increase in d.

The most important criterion is J_c. For an efficient magnet design J_c must be at least 1000 A/mm^2 in the SC (i.e. non-copper), corresponding to an overall J_c of at least 500 A/mm^2. The overall J_c depends on the conductor composition (amount of SC, filament uniformity) and the intrinsic properties (H_{c2}, microstructure).
Thus J_c can be increased by increasing the amount of SC in the cross section or by a stronger flux pinning (Artificial Pinning Center approach).

A large d (large filament or filament bridging), which can be related to the processing method, produces large AC losses and magnetization (i.e. poor field quality). d must be in the range 5 to 10 μm to minimize these effects.

The J_c of both A15 compounds and HTS oxides exhibits sensitivity to stress. Strain sensitivity increases with the magnetic field. The goal for the material is to withstand a tensile strain of 0.5% without permanent degradation.
The use of wind-and-react coil fabrication requires an insulation that withstand the reaction cycle (several hours at 650^{o}C), like fiberglass or a ceramic.

Wire (as opposed to tape) is the preferred strand due to adaptability to various cable design. Moreover the co-winding of tape results in large inductances (poor field quality and AC losses). Nevertheless there might be no other fabrication routes for some materials.

Above 10 T only the A15 compounds Nb_3Sn and Nb_3Al, and HTS oxides $Bi_2Sr_2CaCu_2O_8$ (Bi2212) and $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi2223) approach the J_c criterion in long conductor length and multifilamentary form.

2. COMPOSITE SUPERCONDUCTORS

Nb_3Sn

(T_c=18 K, B_{c2}=22 ¸ 28 T)

Unlike *NbTi*, *Nb_3Sn* is a brittle intermetallic compound having a well defined stoichiometry, which is obtained by long heat treatments at high temperature. In *Nb_3Sn* flux pinning occurs by means of the **grain boundaries**, whose area increases with a small-grained structure (best if less than 40 nm). But heat treatments produce grain growth. In this regard the bronze process is helpful thanks to the copper that enables *Nb_3Sn* to form at lower temperatures than with pure *Sn*.

The APC approach produces smaller grains by inhibiting grain growth or by increasing reaction rates.

The amount of *Nb_3Sn* in the cross section is limited by the *Sn* content in the bronze, which above 15% creates brittle intermetallics.

BRONZE PROCESS	INTERNAL TIN PROCESS	POWDER-IN-TUBE (PIT)
Nb_3Sn in 15% of wire area	*Nb_3Sn* in 18% of wire area	*Nb_3Sn* in 33% of wire area
J_c about 1000 *A/mm^2* at 12T	J_c about 1500 *A/mm^2* at 12T	J_c about 1800 *A/mm^2* at 12T
most developed	potential to increase the amount of SC	most potential to increase the amount of SC
lowest cabling damage	intermediate cabling damage	good for the APC approach
good for the APC approach	cheaper	potentially cheaper
lowest AC losses and d		

BUT

least achievable content of *Sn*	filament bridging	limited filament size
expensive technology		unreacted *Nb* excessive?
		Nb cost?

Nb_3Al

(T_c= 20 K, B_{c2} » 26 T)

It withstands a strain as high as 1%. Unfortunately there appears to be no equivalent of the bronze process for *Nb_3Al*, which means that the conflict between stoichiometry and grain size is severe. A way is to process elemental *Nb* and *Al* in finely subdivided form. At final size the wire is given a very rapid high temperature heat treatment followed by a quench at room temperature, which forms stoichiometric but amorphous *Nb_3Al*. A subsequent heat treatment at lower temperatures is used to grow fine grains of the A15 phase.

Filament diameters are still greater than 50 μm and the high reaction temperatures (1900^{o}C) place severe limitations on coil insulation.

Transverse loading studies on cables haven't yet been performed and although research has been done with powders, by June 1996 no company had yet commercialized a powder process.

JELLY ROLL METHOD	QUENCHED JELLY ROLL	TUBE METHOD (*Nb* tube and *Al* rod)
J_c of 750 *A/mm^2* at 12 T	J_c of 1800 *A/mm^2* at 12 T	J_c of 750 *A/mm^2* at 18 T

BUT

very expensive technologies

BSCCO's

They have high upper critical fields although the field limit for a non-zero transport current in the SC is the so-called *irreversibility field*, which is much lower than B_{c2}.

The key limit to J_c is the connectivity of the grains. Weakly coupled grain boundaries, cracks and imperfect local composition make the current path through the material **percolative**.

J_c is reduced with strain and the behavior is irreversible beyond $0.0\% \leq \varepsilon \leq 0.2 \div 0.4\%$ (there is no compressive range). The upper limit depends on the state of the *Ag*, the amount of pre-compression, and the strength of the *Ag* (that can be strengthened by oxide inclusions).

Another drawback of HTS's is the anisotropy of J_c with respect to the field. In present BSCCO tapes, in a field perpendicular to the tape the J_c at 4.2 K is half than in a parallel field.

The effective filament diameter is large due to bridging during wire heat treatment or to large filaments from wire processing.

***BSCCO 2223* (PIT)**	***BSCCO 2212* (PIT)**
only tape configuration (km)	also round wires (170 m) cheaper higher J_c

3. PRESENT MAGNET PERFORMANCE

- **Twente University Dipole Magnet**

* 1 meter long;
* 192 filament PIT *Nb_3Sn* conductor;
* 5 *cm* single aperture, 2 layer cos(theta);
* fully impregnated Rutherford cables, S-2 fiberglass insulation.

It reached 11 T central field (maximum transverse cable stress greater than 130 *MPa*) on its first quench at 4.2 K (transport current of 18.7 *kA*). After warm-up the quench field increased to 11.3 T in 4 quenches.

There were large field errors due to large effective filaments sizes (40 μm) and large interstrand cable coupling currents. The I_c degradation due to cabling has been about 25%.

From the detected voltages it appears that the limiting factor is not I_c or strain sensitivity, but the inability of the external support structure to maintain enough prestress in the coils.

- **LBNL Dipole Magnet**

* 1 meter long;
* wind-and-react *Nb_3Sn*;
* 5 *cm* single aperture, 2 double-layer;
* fully impregnated, S-2 fiberglass insulation.

It reached 13.5 T central field (peak stress of 140 *MPa*) at 1.8 K (operating current density of 290 A/mm^2), and 12.8 T at 4.4 K. It demonstrated the flexibility and degree of control of the *tensioned wire winding* preloading technique.

Here too it seems that the performance limit was not I_c or strain sensitivity, but a portion of low-field coil not adequately supported.

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