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Journal of Nuclear Materials 283–287 (2000) 968–972

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Russian superconducting materials for magnet systems of fusion reactors

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Abstract

A survey is given of the Russian superconducting materials for the magnet systems of fusion reactors such as 'Tokamak-7', 'Tokamak-15' and ITER. In total, approximately 10 t of superconductors based on Nb–Ti for Tokamak-7 and 26 t of superconductors based on Nb_3Sn (25 t for Tokamak-15 and 1 t for ITER) have been produced. Also reported here are test results of strands produced for the coil-insert conductor for the central solenoid of magnet coils for ITER. The results show small variation in values of critical current, hysteresis losses, residual resistance ratio, and others, which meet the ITER high performance specifications (HP-II). The possibilities of improving critical characteristics by optimization of strand design produced by the bronze and internal-tin process and by processing composite superconductors based on HTSC-compounds have been also considered.

1. Introduction

Superconducting materials with high critical performance are increasingly needed for superconducting magnet systems. One of the large-scale applications of superconductors is in magnets for controlled thermonuclear reactions, such as Tokamak.

About 10 t of Nb–Ti superconductor have been produced for the Tokamak-7 installation, which was the first Tokamak in the world with a superconducting magnet system. The method of galvanic joining was used to wind the conductor [1]. Approximately 25 t of Nb_3Sn superconductor for the Tokamak-15 have been produced in the former USSR. As a result of the Tokamak-15 project, Russian scientists developed and placed into industrial production the processing of Nb_3Sn by the 'bronze' route. The successful start of the Tokamak-15 installation confirmed the suitability of the production methods [2].

Since 1986, when the high-temperature superconductivity (HTSC) phenomena was discovered, research and development (R&D) of HTSC materials based on Y and Bi ceramics with high critical temperatures and magnetic fields have been started in Bochvar institute.

2. Nb_3Sn superconductors produced by the 'bronze' route

Bochvar institute of inorganic materials together with several foreign companies has taken part in the development and production of superconductors for model coils of the ITER magnet system [3]. In accordance with ITER specification, the level of critical current density J_c (non-Cu) for the strands has to be greater than 550 A/mm^2, the hysteresis losses must be less than 200 mJ/cm^3, the residual resistance ratio (RRR) must be greater than 100, 'n' parameter has to be greater than 20 and the Cu/non-Cu ratio must be in the range of 1.4–1.6.

To satisfy these challenging requirements a stabilized Nb_3Sn strand with 7225 filaments artificially doped by Ti in a bronze matrix with high-Sn content (Cu–13.5 wt% Sn) has been developed [4,5]. The performance of these strands has to be confirmed by testing a coil-insert fabricated from them. The coil-insert with a weight of 10

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0022-3115/00/$ - see front matter
PII: S0022-3115(00)00166-5

t and with an external diameter of 2 m and a 5 m height, together with current leads, is being produced by three institutes: Efremov Institute (St. Petersburg), Bochvar Institute (Moscow) and VNIIKP (Podolsk). It will be tested in 2000 in the model coil of the central solenoid (Japan).

Bochvar institute has produced and tested 810 kg of Nb_3Sn strand for this coil-insert. During the final stage, the strand has been plated with a 2 μm Cr-coating in order to reduce AC losses. To test this amount of strand, samples have been taken from both ends of every batch. All investigated strands were heat treated to form of Nb_3Sn as follows: 575°C (150 h) + 650°C (200 h). The critical current was measured by the four-point method at 4.2 K, 12 T, 0.1 μV/cm on cylindrical titanium mandrels 32 mm in diameter with a wire length between potential points of 0.5 m. Hysteresis losses were measured on a vibrating sample magnetometer [6].

Analyses of critical current measurements strand samples results have shown that J_c values are in range of 550–650 A/mm^2 (Fig. 1). The values of hysteresis losses are in the range of 120–200 mJ/cm^3 (Fig. 2) and Cu/non–Cu ratio is between 1.4 and 1.6. The values of RRR are between 92 and 150 (Fig. 3). These characteristics are at

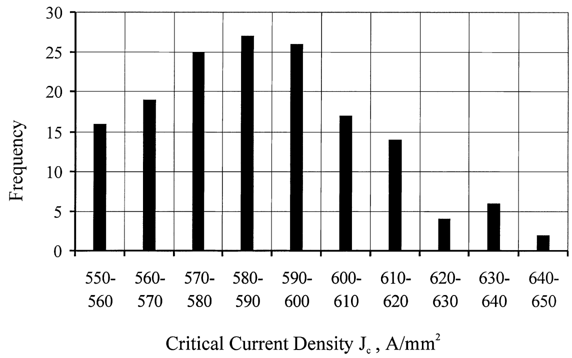

Fig. 1. Distributions of J_c values for the ITER strands.

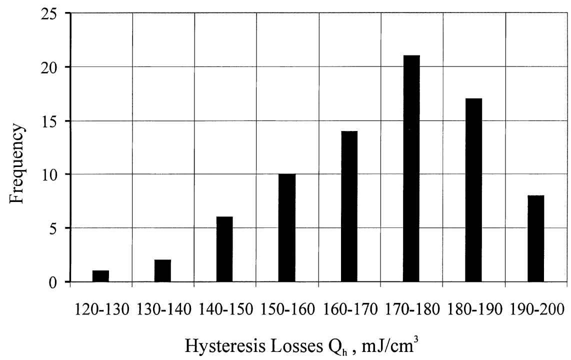

Fig. 2. Distributions of loss values for the ITER strands.

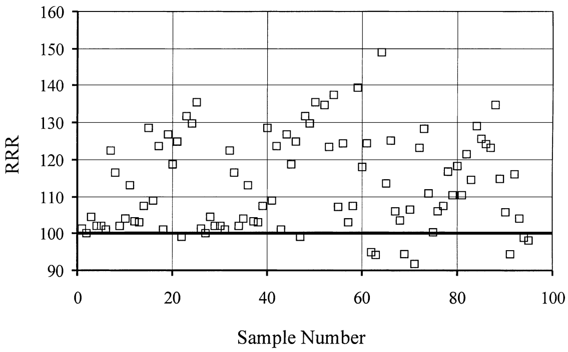

Fig. 3. Distributions of RRR values for the ITER strands.

the required levels. Unit lengths exceed the required level of 1150 m. The parameter n was found to be more than 30 exceeding the ITER specification of 20.

3. Internal-tin Nb_3Sn superconductors

The development and research of the internal-tin Nb_3Sn superconducting strands for the ITER magnet system has allowed us to study the main aspects of internal-tin strand design, which in turn provide an opportunity for considerable improvement of their superconducting properties and industrial production of internal-tin Nb_3Sn strands for large-scale magnet systems.

The experimental superconductor S-12 was developed and produced (Fig. 4 (a)). The strand parameters of that wire are given in Table 1. As a prototype of S-12, Sn–P wire [7,8] was used. The design of the S-12 strand is composed of seven tin plated multifilamentary modules surrounded by a Ta-tube diffusion barrier and external Cu-stabilizer. The Nb filaments of the S-12 strand contained 2 at.% Ti [9]. The multistage reaction heat

Table 1
Parameters and properties of S-12 internal-tin strands

Parameters and properties definition	
Strand diameter (mm)	0.6
Volume fraction of Cu stabilizing (%)	27
Number of Nb(Ti) filaments	3673
Diameter of Nb(Ti) filaments (μm)	4.6
Spacing between filaments (μm)	1.1
Doping Nb filaments by Ti (at.%)	2
Volume fraction of Nb (inside barrier) (%)	33.4
Volume fraction of Sn (inside barrier) (%)	19.8
J_c (non-Cu; 0.1 μV/cm; 4.2 K) (A/mm^2)	
– in magnet field 10 T:	3090
– in magnet field 12 T:	2070
B_{c2} (by Kramer plot), T	26.4

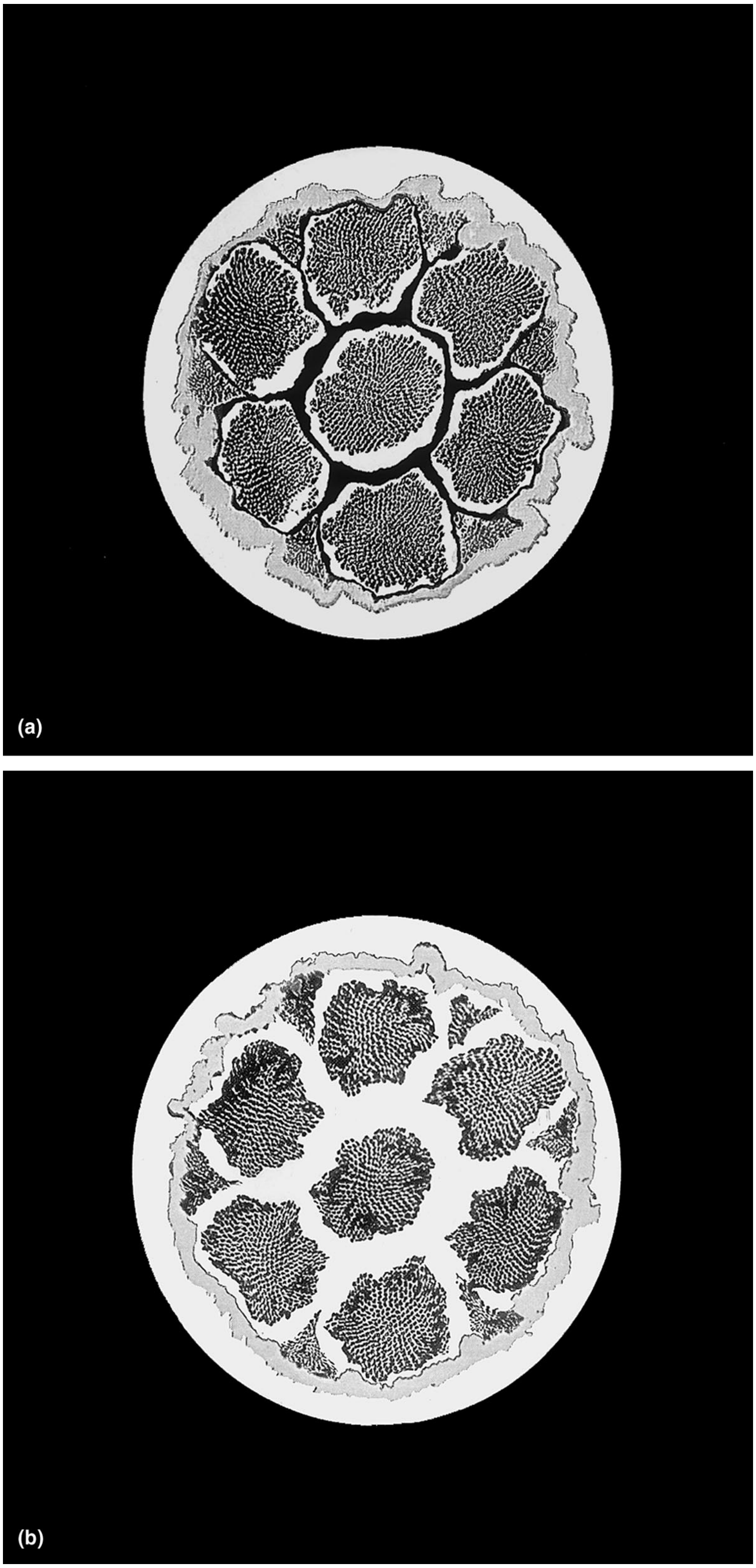

Fig. 4. Cross-section of the internal-tin strand S-12: (a) before heat treatment; (b) after reaction to heat treatment.

treatment to form Nb_3Sn (Fig. 4 (b)) was performed in vacuum. Results of J_c measurements are presented in Table 1.

Compared to Sn–P various improvements were made in S-12 wire layout. A high critical current density (up to 2070 A/mm^2) was obtained on the non-Cu cross-section at 12 T. This value could be explained by the extremely fine grained structure of Nb_3Sn layers in S-12 wire, about 50–60 nm.

4. Nb–Ti superconductors

It is assumed that large cross-section 'cable-in-conduit-conductor' (CICC) based on Nb–Ti strands will be used for the windings of the ITER poloidal magnet system. Such CICC superconductors are made from multistage twisted superconducting strands housed in stainless steel conduit. Superconductors working in a pulsed field have to possess the unique combination of high J_c (3000 A/mm^2 at 5 T), high value of n parameter (greater than 40 at 5 T), high RRR (>100) and low energetic losses with constant time ~7 ms.

R&D on design and processing of Nb–Ti superconductors is being carried out at Bochvar institute [7]. By the application of low temperature extrusion, the samples of wire have been made from high-purity Nb–Ti alloys with J_c 3000 A/mm^2 at 5 T and n parameter not less than 80, and samples of wire on base NbTiTa alloy with J_c 1700 A/mm^2 at 10 T have been also produced.

Currently Bochvar institute started to produce 0.5 t of Nb–Ti superconductors for ITER. In the process of this work, various wire designs with diameter 0.75 mm and filament diameter 6–7 μm, including wires with low filling factor (less than 20% Nb–Ti) have been examined. Also to reduce hysteresis losses, resistive barriers composed of Cu–Ni alloys have been inserted in the wire layout (Fig. 5). To reduce coupling losses of conduit, the technology of Ni-coating was developed. In order to conduct comparable tests, the cable Institute VNIIKP will produce three pieces of cable with 15 m length of various layouts obtained in Bochvar institute.

5. High-temperature superconductors

In Bochvar institute, R&D activity is performed on composite long-length wires and tapes as well as bulk materials based on HTSC compounds. In magnetic fields higher than 10–12 T at 4.2 K, the J_c values for Bi-2223 tapes have been found to be greater than J_c for Nb_3Sn wires [10,11]. For current lead applications, in

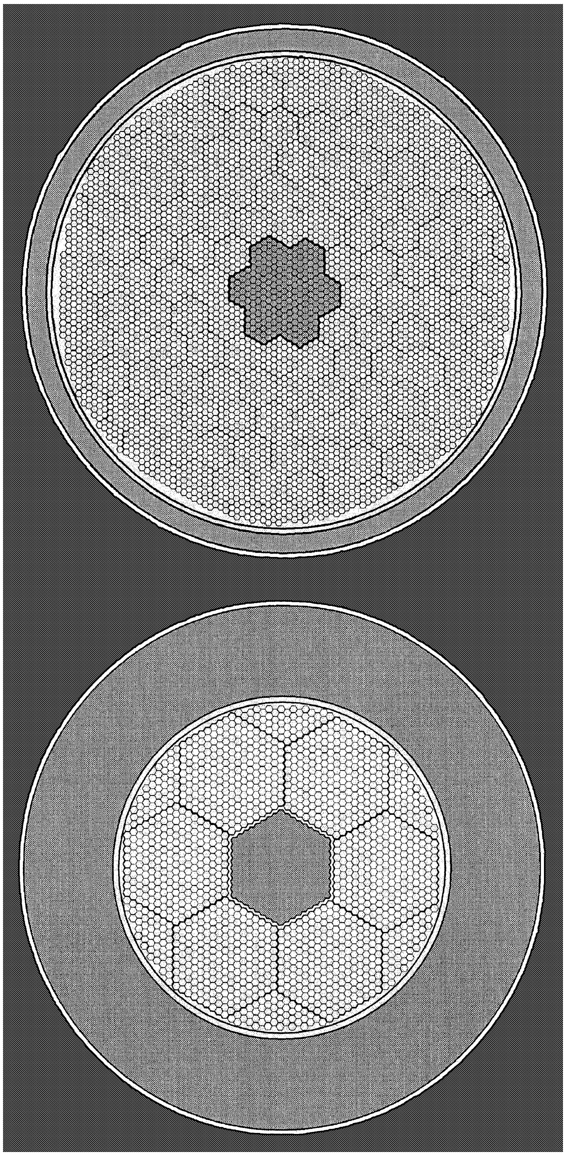

Fig. 5. Designs of the Nb–Ti wire.

61 filaments

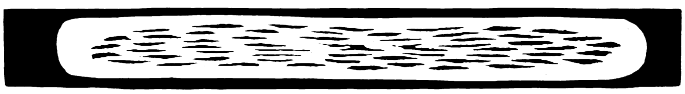

Fig. 6. Cross-section of the Bi-2223/AgAu strand.

the absence of high fields, HTSC elements are desirable due to the superconductivity over a wide temperature range (4.2–77 K).

The main efforts have been directed at the development of long-length HTSC composite conductors, which are more stable under mechanical and cyclic thermal deformation and, as consequence, make it possible to create reliable electrical devices [12,13].

As a result of technological optimization and the developments of optimal wire design, Bi-2223 based tapes have been made an Ag–Au sheath up to 250 m in length (Fig. 6). In collaboration with SSC 'Kurchatov institute' and institute of high energy physics (Protvino), several models of 1 kA current leads have been produced and tested. The results achieved will allow the production of commercial current leads.

6. Conclusions

- The amount of 810 kg Nb_3Sn strand which meets ITER requirements has been produced and tested.
- The experimental internal-tin Nb_3Sn superconductor with critical current density J_c more than 2000 A/mm^2 at 12 T, 4.2 K, 0.1 μV/cm have been developed and produced. This result is higher than the J_c for conventional ITER strands by a factor of 3.
- The Nb–Ti strand for ITER poloidal magnet system has been developed and production of 0.5 t Nb–Ti superconductors for ITER has started.
- HTSC for current leads for fusion installations has been developed. HTSC-insert models in 1 kA current leads have been produced and successfully tested.
- LTSC and HTSC materials developed to date have properties that meet requirements for magnet systems and current leads of existing projects of fusion.

Acknowledgements

The authors would like to thank Mr N. Cheverev, Mr V. Korzhavin (RF ministry of atomic energy), Dr O. Filatov, Dr S. Egorov (Efremov institute, St.-Petersburg), and Dr V. Sytnikov (VNIIKP, Moscow) for their participation in the work and for many valuable discussions on the results, particularly in relation to the ITER project.

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