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Development of the superconductors for ITER magnet system

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Abstract

A review is given of the present status of the development and production of Nb_3Sn and Nb–Ti superconductors for the Model Coils and the real Magnet System of the International Thermonuclear Experimental Reactor (ITER) in the Russian Federation Home Team. It is shown that Nb_3Sn bronze processed superconductors produced for the Model Central Solenoid Coil insert meet the ITER joint Central Team requirements. In particular, the critical current density, measued in non-Cu area is not less than 550 A/mm^2 for 12 T at 4.2 K, the level of hysteresis losses is not in excess of 200 mJ/cm^3, and the Cu-stabilizing shell resistivity ratio of Cr-plated wire is 150. Internal tin Nb_3Sn superconductor development and test results are presented, confirming the possibility of their application for the ITER Magnet System winding. Nb–Ti superconductors for PF coils properties have also been considered. The possibility of Nb_3Sn and Nb–Ti superconductor manufacture with the use of large composite billets up to 300 mm in dia is shown, creating the possibility for large scale industrial production (several tens of tons/year) of these materials for the ITER Magnet System.

1. Introduction

Since about 30 years when it was shown that the critical properties of contemporary supporconductors became acceptable for their application in technical devices, their development in this direction has been under thorough consideration in Russia. In particular, the development of large scale magnetic systems based on superconducting materials, which is critical for the creation of thermonuclear fusion facilities of the Tokamak-type, is among the most important activities.

The first magnetic system based on Nb–Ti superconductors for Tokamak facility (Tokamak-7) was successfully constructed as early as in 1978. The next very important step took place in 1988 when a magnetic system based on Nb_3Sn superconductors was constructed and successfully tested for Tokamak-15. The realization of such large scale projects, which assumes the production of tens of tons of high quality superconductors became feasible due to the development of the technology and the organization of industrial production of these unique materials.

The experience gained in the Russia on the application of Nb–Ti and Nb_3Sn suprconductors as a winding material for magnetic systems in domestic fusion facilities has to a significant extent provided the impetus for making a positive decision on the development of superconducting magnetic systems for the International Thermonuclear Experimental Reactor (ITER). Nowadays Russia is participating in the development and the production of the superconductors for the model coils of the ITER project and is carrying out preliminary preparations for the organization of the large scale industrial production of the superconductors for the real magnetic system of the ITER, the total required amount of which is equal to 1700 tons.

This work is devoted to a review of the results obtained during extensive research on the development of Nb_3Sn bronze processed superconductors designed for application in the insert to the central solenoid model coil, and also on the development of the internal tin Nb_3Sn superconductors assumed to be used as winding wire for toroidal field coils, and on the Nb–Ti superconductors for poloidal field coils.

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2. Nb_3Sn bronze processed superconductors

In Russia the Bochvar Institute of Inorganic Materials is fabricating the bronze processed strand for the construction of the insert to the model central solenoid coil.

Until the time of companies to produce the strands (in 1933) no signal industrial company had experience in the manufacture of Nb_3Sn strands with the required properties to meet the whole set of the ITER requirements (Table 1). Therefore, before initiating, the fabrication of strands required it was necessary to create the strand's design, to optimize the composition of the initial materials and to modify the manufacturing process in order to attain the necessary level of superconducting properties.

The experimental investigations on the model short length strands have shown that the reduction of the Nb filaments diameter resulted in a significant increase of the critical current density mainly by the refinement of grain structure in the Nb_3Sn layers. But at the same time due to the decrease of the distance between the filaments (~0.8 μm) the proximity effect has risen accompanied by an increase of hysteresis losses [1].

An effective way to increase the Nb_3Sn critical current density is connected with the enhancement of tin content in a bronze matrix and with doping of some components of the composite strand. That is why the decision was taken to increase the tin content in a bronze matrix up to 13.5 wt%, and to introduce Ti in the filament material. Doping by Ti was realized by the method of "artificial doping" [2] thus avoiding the poor workability problems in Nb–2% Ti alloy connected with traditional metallurgical alloying. Artificial doping of Nb filaments assumes that instead of the rods made from Nb–2% Ti alloy, the Nb tubes with inserted Ti or Nb–Ti alloy rods are used as a composite filament [3]. The subsequent operations were traditional for the "bronze technique". This modification of the manufacturing process allowed the high level of workability of the initial components Nb and Ti to be maintained, and the interdiffusion of both elements took place only at the stage of the final heat treatment, just simultaneously with the formation of the superconducting Nb_3Sn phase.

Table 1
ITER strand specifications

	HP I	HP II
Non-Cu J_c, A/mm$_2$, (12 T, 4.2 K, 0.1 μV/cm)	>700	>500
Non-Cu hysteresis losses, mJ/cm^3, (±3 T)	<600	<200
n value, (12 T, 4.2 K)	>20	
Strand diameter, mm	0.81	
Cu/non-Cu ratio	1.4–1.6	
Twist pitch (right hand), mm	8–11	
Unit length, m	>1150	
RRR (at 0 T, 273-18K)	>100	
Cr plating thickness, μm	2–3	
Final stage of heat treatment	650°C-175 h	
Total time of heat treatment	<400 h	

It was revealed that the level of Cu stabilized strand hysteresis losses to a great extent were dependent on the materials and the form of diffusion barriers [4]. The highest level of hysteresis losses was obtained for the strands with a Nb diffusion barrier due to the formation of extensive areas of Nb_3Sn layers on the Nb barrier's surface facing the bronze matrix. The lowest level of hysteresis losses was measured for the strand with a Ta diffusion barrier. The use of a two layered Nb–Ta diffusion barrier eliminated the reaction of Nb with the bronze matrix together with ther reduction in the strand cost.

As a result of the investigations conducted, a strand with 7225 filaments was designed. The cross section of this strand is presented in Fig. 1. The properties of the designed strand met the ITER specification [5,6]. Nowadays the fabrication of this strand in the required amount for the construction of the toroidal field insert in central solenoid model coils (~1 ton of strands) is being finished. The non-Cu critical current density of the strands designed is in the range of 550–570 A/mm^2 (12 T, 4.2 K); the hysteresis losses are in the range of 140–200 mJ/cm^3.

In Russia during the fabrication of the strand expected to be used for the model coils, final composite billets of 95 mm in dia were used. For the production of the strand for the real coils of the ITER magnetic system much larger quantities of the strand will have to be manufactured – up to several tens of tons per year. The necessity to increase the production rate, to improve the

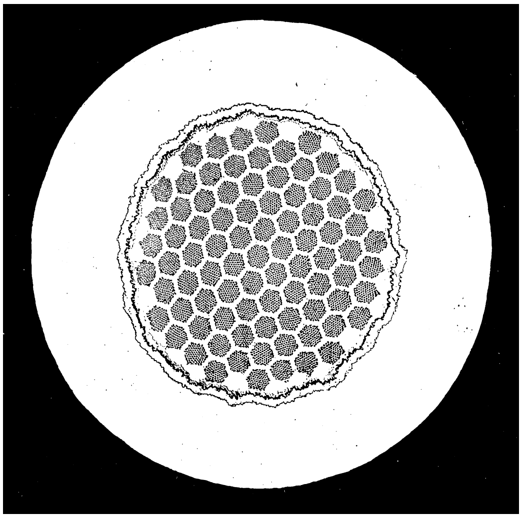

Fig. 1. Cross section of the bronze processed Nb_3Sn strand with 7225 filaments, produced from the final composite billet of 95 mm in diameter.

technical and economic efficiency of the manufacturing process has demanded investigations on the possibility of using large scale final composite billets with a diameter up to 315 mm. The theoretical unit length of the strand produced from this billet is equal to 60 km. In order to test the new technological process two strand designs were chosen. The first design completely repeated the design which was already used for the production of strand for ITER model coils, and contained 7225 filaments and 60% of outer stabilizing copper. The second design was optimized by increasing the filament number up to 13,969. The investigations have shown that a factor of 20 increase in the weight of the billet did not cause a lowering of the superconducting properties. For the strand with 7225 filaments the non-Cu critical current density (J_c) at 12 T and 4.2 K was equal to 570 A/mm^2 and for the strand with 13,969 filaments $J_c = 650$ A/mm^2, which was slightly higher than the average level of J_c typical for the strands produced out of the billets 95 mm in diameter. The hysteresis losses for the strands with 7225 filaments and 13,969 filaments were equal to 160 and 200 mJ/cm^3, respectively [5].

Alongside the production of the strand for the ITER model coils, investigation on the further optimization of the design and manufacturing process were being carried out. Strands enhanced with up to 12,684 number of filaments were designed. The peculiar feature of this strand was in the design of artificially doped filaments, each of which contained not one but four inserts made of the Nb–Ti alloy HT-50 [7]. The diffusion barrier separating the stabilizing Cu and non-copper area of the strand was made of single layer Ta (Fig. 2). As a result of the strand's design optimization J_c was increased up to 750 A/mm^2 (12 T, 4.2 K) and hysteresis losses were diminished to 100 mJ/cm^3 [7]. It could be stated that the strand developed meets both HP-1 and HP-II ITER specifications (Table 1) simultaneously and that this strand may be used both for the toroidal field coils and for the central solenoid.

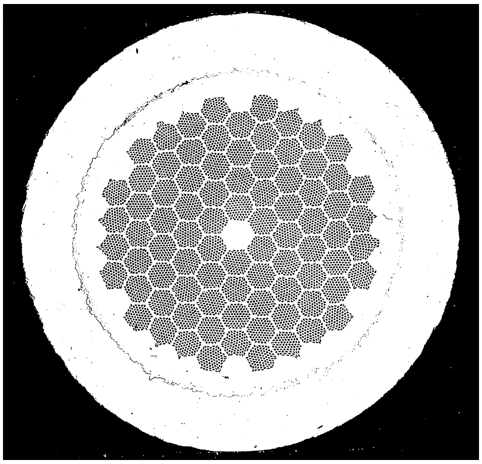

Fig. 2. Cross section of the advanced bronze processed Nb_3Sn strand with 12,684 filaments.

3. Internal tin Nb_3 Sn superconductors

Considering the application of internal tin conductors as a strand for the ITER Magnet System one should keep in mind that these strands have some peculiar features which make them to be quite different compared with bronze processed strands. Because the tin necessary for Nb_3Sn intermetallic compound formation is inserted into the conductor as a pure metal or as an alloy, the Nb filaments have to be arranaged in the copper matrix with the spacing between them less than in the bronze processed conductors, where the Nb filaments are arranged uniformly in a Cu–Sn solid solution alloy. The smaller distance between the Nb filaments do not influence the critical current which is determined mainly by the quantity and quality of the superconducting phase. In fact we have succeeded in attaining J_c up to 510 A/mm^2 in 16 T and 210 A/mm^2 in 18 T for a single core internal tin conductor [8]. But the main disadvantage which arises from the lesser spacing between the Nb filaments, is connected with the much larger values of hysteresis losses in such kind of conductors [9]. The hysteresis losses in internal tin model strands confirming the dramatic increase of the level of losses as the spacing was decreased to less than 1 μm are shown in Fig. 3 [10].

In the process of developing of the internal tin conductor for ITER we also used the results of our investigations on the processes which took place during the multistage reaction heat treatment [11]. Two designs of internal tin strands were developed, referred further as "Sn–P" and "Sn–S" conductors. The cross sections of these strands are presented in Fig. 4(a) and (b). The geometrical parameters of both strands are presented in Table 2. The results of superconducting property mea-

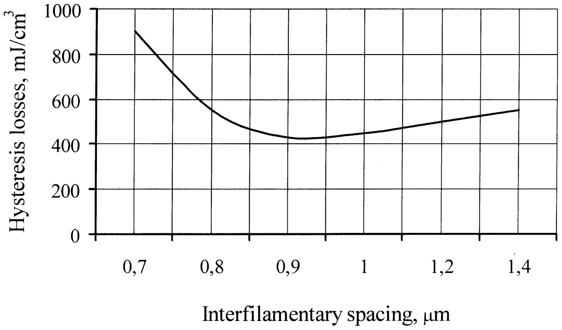

Fig. 3. Hysteresis losses vs. distances between the filaments in the internal tin Nb_3Sn strand with 13,566 filaments.

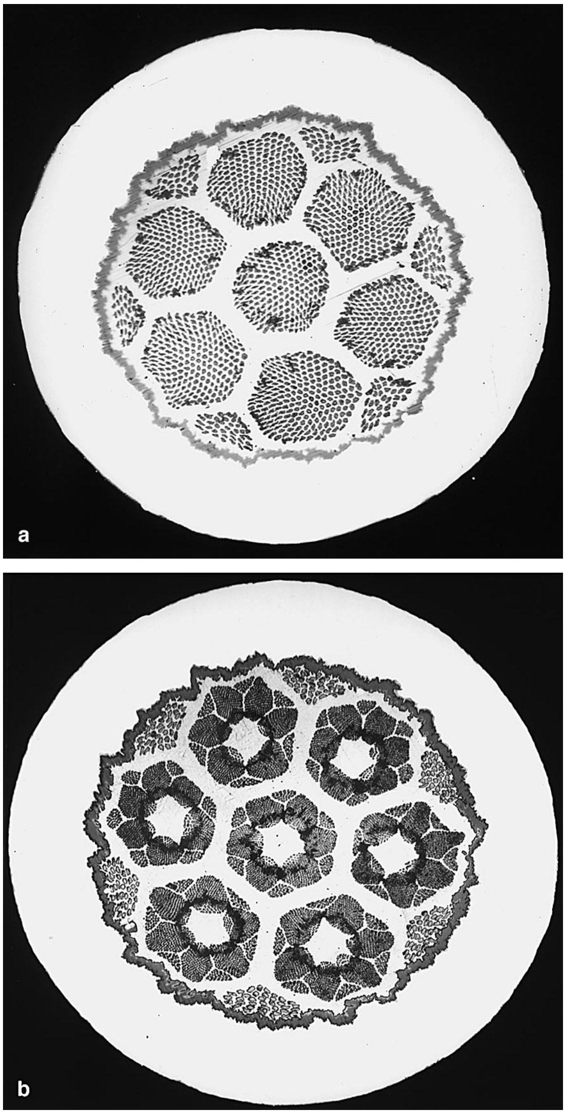

Fig. 4. Cross sections of the internal tin Nb_3Sn strands after reaction heat treatment: (a) the design Sn–P; (b) the design Sn–S.

surements for both strands are summarized in Table 3. Values calculated in accordance with ITER recommendations on critical current density at 13 T and at 6.5 K are also given. The results obtained confirm that the designed internal tin strands meet both the ITER requirements HP-1 and HP-2.

4. Nb–Ti superconductors

The Bochvar Institute of Inorganic Materials in cooperation with Russian Industrial Enterprises has been developing and manufacturing Nb–Ti and Nb–Ti–Ta conductors for various applications. Such conductors are produced in copper and copper based (Cu–Ni, Cu–Mn) matrixes with diameters from 0.1 mm up to cross sections of ~30 mm^2.

In Russia, especially for the large scale accelerating storage facility (YHK), a Nb–Ti superconductor was designed and the process of its industrial manufacture was developed. The parameters of this conductor are presented in Table 4 (column 2) and its cross section is given in Fig. 5. The large scale industrial production of this strand (120 tons) was organized including the fabrication of a representative amount of strand with the use of large scale final composite billets.

The creation of new fields of Nb–Ti superconductor application, in particular for large scale magnetic systems, results in a further increase of requirements for their properties, design and unit lengths. Beside the increasing requirements to J_c, there are also demands to improve stability and energy losses in the Nb–Ti strands. This leads to a necessity to increase the ratio of Cu/non-Cu, to decrease the diameter of the filaments, and at the same time maintaining the high level of filaments geometrical homogeneity, which is determined by including a requirement on the parameter $n > 40$ for the ITER Nb–Ti strand. In some cases the use of composite matrix material instead of copper is also necessary. After the optimization of the design and manufacturing process, Nb–Ti strands were produced which met the more strict requirements on the wires for the LHC (CERN) magnet

Table 2
Parameters of Sn–P and Sn–S internal tin strands

Parameters definition	Sn–P	Sn–S
Volume fraction of stabilizing Cu, %	57	53
Number of Nb(Ti) filaments	1699	10638
Diameter of Nb(Ti) filaments, μm	6.8	2.1
Spacing between filaments, μm	2.5	0.8
Volume fraction of Nb (inside diffusion barrier), %	28.4	24.2
Volume fraction of Sn (inside diffusion barrier), %		
in Sn layers	16.4	8.0
in Sn cores	–	8.4

Table 3
Superconducting properties of Sn–P and Sn–S internal tin strands

Strand; ø mm	J_c, A/mm^2 4.2 K; 12 T 0.1 μV/cm (non-Cu)	J_c, A/mm^2 6.5 K; 13 T 0.1 μV/cm (non-Cu)	n	B_{c2}, T	Q_c (±3 T), mJ/cm^3 (non-Cu)
Sn–P; ø 0.81	722	354	21	28.3	170
Sn–S; ø 0.81	703	328	15	26.7	370
Sn–P; ø 0.6	758	375	22	28.7	–

Table 4
Parameters of Nb–Ti superconductors

Parameters definition	Strand for YHK	Strand for LHC	Strand for "ITER" (Requirements)
Strand's diameter, mm	0.85	0.85	(0.75–0.85) ± 0.003
Filament's diameter, μm	6	<10	<6
Cu/non-Cu ratio	1.4/1	1.8/1	(1.2–1.5) ± 0.05/1
J_c at 5 T; 4.2 K, A/mm^2	2750	3000	3000
"n" parameter	–	–	>40
RRR	–	>100	>100
Twist pitch, mm		<10	10 ± 2

system. The parameters of this strand are presented in Table 4 (column 3) and its cross section is given in Fig. 6. The developed Nb–Ti strands, and the process of their manufacture which were successfully verified by industrial production, had been accepted as the basis for the development of the Nb–Ti strands for the ITER coils. In fact the requirements on the ITER Nb–Ti strands (see Table 4, column 4) are substantially close to ones typical for the wires for accelerator magnets. One of the variants of the Nb–Ti strand designed especially for an application in the magnetic system of "Tokamak"-type facilities is presented in Fig. 7.

It should be noted that rather high ITER requirements on the critical current density will demand some additional adjustments in refining the design and manufacturing process to attain a reasonable production rate for the large scale industrial production.

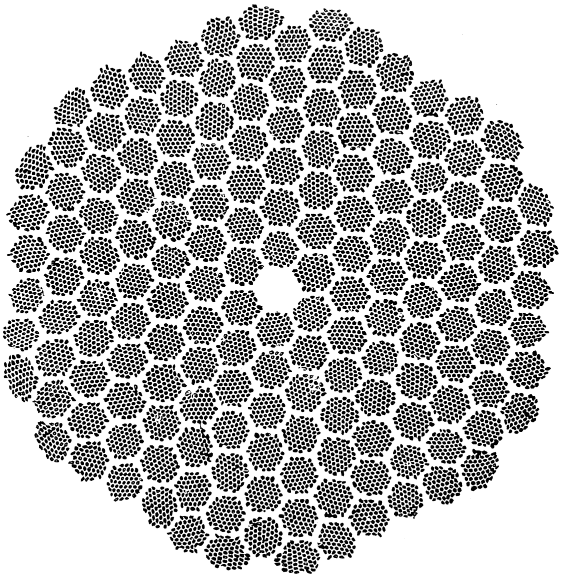

Fig. 5. Cross section of the Nb–Ti strand designed for the accelerating – storage facility YHK.

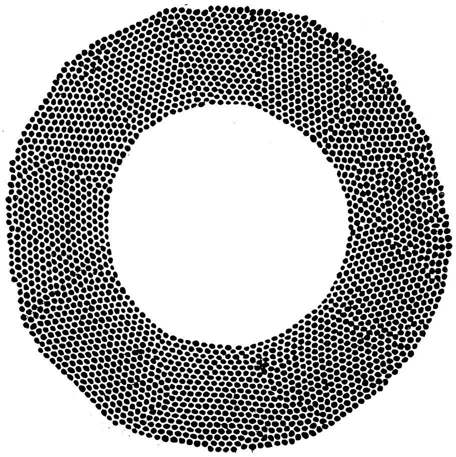

Fig. 6. Cross section of the Nb–Ti strand designed for application in accelerator magnet system "LHC" (CERN).

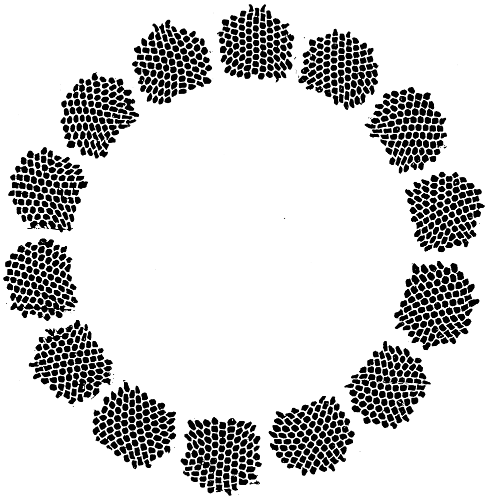

Fig. 7. Cross section of the Nb–Ti strand designed for the application in fusion reactors of Tokomak type.

5. Conclusion

- Bronze processed Nb_3Sn strands that have been developed meet all the set of HP-II ITER requirements. The developed industrial scale manufacturing process was verified by the production of 1 ton of the strands
- Investigations on the bronze processed Nb_3Sn strands have shown the possibility of further enhancement of the non-Cu critical density without any substantial change in strand design and manufacturing process.
- The developed internal tin Nb_3Sn strands meet both HP-I and HP-II ITER requirements.
- The properties of the developed Nb-Ti strands equal the requirements imposed on the Nb–Ti strands intended for use in the ITER magnetic system.
- The possibility of producting strands which meet the ITER requirements by using large scale final composite billets up to 300 mm in diameter has been shown.

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References

[1] A. Shikov, L. Fisher, I. Voloshin, A. Chukin, A. Vorobjova, Losses in Multifilamentary Nb_3Sn wires – IV Soviet – German Seminar on High Temperature Superconductivity, 1991, pp. 307–311.
[2] A.D. Nikulin, A.K. Shikov, A.E. Vorobieva et al., Adv. Cyrogenic Eng. 42 (1996) 1337.
[3] A.K. Shikov, A.E. Vorobieva, A.G. Silaev et al., The method of Nb_3Sn composite superconductor fabrication, RF Patent Application N 94 – 023625/07 (022587) of 21.06.94 .
[4] A.D. Nikulin, A.K. Shikov, A.E. Vorobieva et al., Investigation of the Nb_3Sn wires design parameters and twist pitch influence on hysteresis losses, Presented at CEC/ICMC – 97, Portland, USA, 1997.
[5] N. Mitchell, P. Bruzzone, M. Spadoni, M. Nishi, A. Shikov, J. Minervini, IEEE Trans. Appl. Superconductivity 5 (1995) 905.
[6] P. Bruzzone, H.H.J. ten Kate, M. Nishi, A. Shikov, J. Minervini, M. Takayasu, Adv. Cyrogenic Eng. 42 (1996) 1351.
[7] A.K. Shikov, A.D. Nikulin et al., Improvements on the $(NbTi)_3Sn$ bronze processed superconductors performance, in: Proceedings of the ECUAS Conference Netherlands, 1997.
[8] V.I. Pantsyrnyi, A.K. Shikov, I.I. Davydov et al., IEEE Trans. Magn. 27 (1991) 2518.
[9] A. Shikov, J. Nucl. Mater. 233 (1996) 120.
[10] V.I. Pantsyrnyi, A.K. Shikov, A.D. Nikulin et al., IEEE Trans. Magn. 32 (1996) 2862.
[11] V.I. Pantsyrni, A.D. Nikulin, A.K. Shikov et al., IEEE Trans. Magn. 28 (1992) 866.