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DEVELOPMENT OF INTERNALLY STRENGTHENED PREREACTED Nb_3Sn SUPERCONDUCTORS

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Résumé - Les critères d'élaboration pour des conducteurs de Nb_3Sn préréagis et avec renforcement interne, ainsi que les propriétés supraconductrices à haut champ de conducteurs avec différents matériaux de renforcement sont présentés.

Abstract - Design criteria for a prereacted, internally strengthened Nb_3Sn conductor and the superconducting properties in high fields of conductors with different reinforcing core materials are presented.

INTRODUCTION

A 10 T - 1.2 K superconducting solenoid with a clear bore of 390 mm is to be rated up in magnetic field by at least 2 Tesla by means of a Nb_3Sn -insert coil. A reasonable operational current density of $6.5 \cdot 10^3 \text{ A/cm}^2$ in the conductor leads to the following size of the insert coil: 300 mm i. dia., 380 mm o. dia. and a length of 400 mm. A prereacted Nb_3Sn conductor must be used in the windings for forming cooling channels to warrant a sufficient electrical stability by LHe-ventilation. The Lorentz forces of 150 N/mm^2 in the coil require a mechanical reinforcement of the conductor. A compacted monolith configuration with a central steel core seemed to be a reasonable solution. 1),2)

THE CONDUCTOR CONFIGURATION

The geometric size of a prereacted Nb_3Sn conductor is not only determined by the operational current, but the thickness of the conductor is determined by the strain occurring by bending during the winding of a coil. The Nb_3Sn conductor will be damaged irreversibly at strains exceeding 0.6 %, as shown by Kuckuck et al³⁾ and Rupp⁴⁾. The tensionless state of a long length of such a conductor is a bent one, because the heat treatment has to be made on a spool. From this state, the conductor will be straightened and rebent again and experiences strain and compression during the processing, so that the final geometric size is a compromise regarding all the steps of handling. Thus, for a final bending diameter of 300 mm and a heat treatment diameter of 600 mm, a conductor thickness of 3.5 mm seemed to be tolerable, in particular under the aspect that the

distance of the Nb_3Sn filaments from the neutral axis is smaller than 1.75 mm, which can be seen in Fig. 1 (a). The final strain ϵ between heat

Fig. 1 (a)

Fig. 1 (b)

Fig. 1:
The final size of the conductor (a); the conductor in the first stage of compaction (b).

treatment radius r_1 and coil radius r_2 corresponds to the formula $\epsilon_s = a[1/r_2 - 1/r_1]$ with the distance a between outermost² filaments and the neutral axis. For the present conductor the expected strain value will be 0.46 %.

Fig. 1 (a,b) show a cross section through the final compacted monolith of $3.5 \times 5 \text{ mm}^2$ and a slightly compacted version after the encapsulation into the outer copper sleeve. The strands contain 64 % copper and are protected by a Ta-diffusion barrier. Because the strengthening material experiences also the heat treatment of the Nb_3Sn , it must be a creep resistant material to keep sufficiently high yield strength. In the prototype conductors steel A 286, inconel, a molybdenum alloy, TZM, and from reason of comparison copper were used as core materials. They differ considerably in the thermal contraction coefficient $\alpha[^\circ\text{C}^{-1}]$ e.g. at room temperature $17.8 \cdot 10^{-6}$ for A 286, $14.9 \cdot 10^{-6}$ for inconel, $4.9 \cdot 10^{-6}$ for TZM and $16.7 \cdot 10^{-6}$ for copper. The steel A 286 was favoured, because the hardening heat treatment could be made in combination with the Nb_3Sn heat treatment. The other core materials were included in the investigations to study the influence of the different thermal contraction on the current density.

The composite conductor should fulfil the following requirements:

Cross section	$q = 3.5 \times 5 \text{ mm}^2$
Critical current	$I_c = 1750 \text{ A}$ ($0.5 \mu\text{V/cm}$ at 10 T and $T = 4.2 \text{ K}$)
Yield strength	$\sigma_{0.1} = 150 \text{ N/mm}^2$
Cu/non-copper ratio	$\text{Cu/bronze} > 3$
Twist in strand	50 mm
Transposition in cable	100 mm

From empirical data of current density, a content of 20 % $\text{Nb}_3\text{Sn} + \text{bronze}$ in the cross section should be sufficient. A subdivision of the remaining area into a copper and a steel part can only be made very crudely by simplifying assumptions. The mixing rule, assuming steel to behave elastically, copper and bronze being in the plastic regime and contributing to force carrying by 80 N/mm^2 and 150 N/mm^2 respectively, gives a steel fraction of 12 %. The composition of 20 % Nb_3Sn -bronze, 68 % copper and 12 % core material could not be achieved in all the samples because all the core materials were not available in the right dimensions.

CRITICAL CURRENT VALUES

Fig. 2:
The critical currents I_c versus magnetic field B of the Nb_3Sn conductor with different core materials.

The critical currents were measured in one layer "wind and react" coil sample over one turn at least, i.e. 29 cm, whereas the total number of turns was four. The I_c values were defined for a voltage drop of $0.5 \mu\text{V/cm}$ and determined up to fields of 10.5 T. Because the bare conductor was well cooled by the liquid helium environment, the conductor was tested far into the current sharing regime where heat fluxes up to $7 \cdot 10^{-2} \text{ Watts/cm}^2$ occurred.

Fig. 2 shows the critical current values for the Nb_3Sn conductors with the different strengthening cores. The conductor with the copper core can serve as the basis for comparison, because the composition of Nb_3Sn , CuSn -bronze and copper corresponds to the usual arrangement in multifilamentary Nb_3Sn conductors. Obviously the current densities decrease with increasing thermal contraction coefficient of core material as was expected.^{5),6)} Also in the slightly compacted state the compacted cable showed the same reduction in I_c as in case of 100 % compaction comparing e.g. the A 286 core conductor with the copper core conductor. The current sharing regime in these Nb_3Sn conductors is very much extended and covers between a voltage drop of $0.5 \mu\text{V/cm}$ to $33 \mu\text{V/cm}$ an increase of current of about 700 A. The copper matrix contributes only about 70 A to the current carrying capacity. Some typical data in

Tab. I: The critical current I_C , current I_{CS} in the current sharing regime, I_{Cu} the current in the copper matrix and the corresponding resistivity ρ in the Nb ₃ Sn/bronze cross section at 10.5 T.	Core	I_C [A] 0.5 μ V/cm	ρ_c [Ω cm]	I_{CS} [A] 33 μ V/cm	I_{Cu} [A]	ρ_{CS} [Ω cm]
	Cu	1750	$9.5 \cdot 10^{-12}$	2465	82.5	$4.66 \cdot 10^{-10}$
	TZM	1500	$1.11 \cdot 10^{-11}$	2233	77.5	$5.14 \cdot 10^{-10}$
	Inconel	1317	$1.26 \cdot 10^{-11}$	2000	77.5	$5.76 \cdot 10^{-10}$
	A 286	875	$1.9 \cdot 10^{-11}$	1542	70.4	$7.0 \cdot 10^{-10}$

the current sharing regime are compiled in Tab. I. The extended current sharing regime indicates that the Nb₃Sn in this conductor can be operated steadily beyond the critical current value in a relatively high resistive state. The logarithmic increment α of the increase of resistivity with transport current ($\rho = \rho_0 \exp[\alpha \cdot (I - I_0)]$) has the same value $6.04 \cdot 10^{-3}$ [A⁻¹] for all the configurations. In comparing the critical current of strain influenced conductors it might be more convenient to use an I_C definition on the base of the resistivity of the superconductor in the non-copper cross section instead of a voltage/cm-definition, because that is likewise correlated to an internal physical property. Thus, a resistivity value of $\rho = 10^{-11}$ Ω cm of the superconductor in the bronze cross section, a value sometimes used, would leave unchanged the I_C value in the case of the copper core but decrease the I_C value from 875 A down to 770 A in case of the A 286 core.

THE CURRENT SHARING STATE IN DEPENDENCE ON MAGNETIC FIELDS

The high field part of the coil could be run in the current sharing state if the available cooling power would be sufficient. An estimation of the losses to be expected needs the knowledge of current sharing behaviour in dependence on the magnetic field. Measurements of the current sharing voltage at constant current in a decreasing magnetic field give in a first approximation an exponential relationship for the resistivity $\rho = \rho_0 \exp[-\gamma \cdot (B_0 - B)]$ with a logarithmic decrement $\gamma = 1.98$. From that, a mean resistivity for the total coil can be derived taking into account the field change over the coil.

$$\bar{\rho} = \frac{\rho_0}{\Delta B_r \cdot \Delta B_z} \int_0^{\Delta B_r} \int_0^{\Delta B_z} \exp[-\gamma (B_r + B_z)] dB_r dB_z$$

The losses of the insert coil mentioned before would be 3.6 Watts if it operates at a voltage of 0.5 μ V/cm and a current level of 1350 A, i.e. at critical current, in the high field windings. This demonstrates that the current sharing regime cannot be used in a steady operation mode.

TRIAL WINDINGS

About 5 m of different conductor samples were heat treated on a 600 mm diameter spool at 700° C for 120 h and from that wound onto a sample coil of 300 mm. The four windings were wound tight to the bore tube and insulated from turn to turn by a capton foil. The outer side of the conductor was wetted by liquid helium.

The investigations were performed in the 390 mm bore of the magnet mentioned before at 4.2 K up to 8 T. The Lorentz forces cause tensile or compressive forces on the conductor depending on the direction of sample current ($\sigma = \pm j \cdot B \cdot r$). The compressive forces in particular are supported by the bore tube so that the conductor has to carry no forces. First the critical current values of the conductors were determined in the force free mode and then under tensile forces. Pure bending caused a reduction in critical current between 10 and 15 % compared to values gained from the "wind and react" samples. This must be deduced from the tensile and compressive forces occurring in the curved conductor which do not compensate due to the non-linearity of the stress effects.⁶⁾ Even in twisted and transposed conductors there is no balance by bypass currents because of the resistivity of the matrix. In any case, bending will lead to a certain reduction in critical current.

The effects of bending and tensile load on the conductor are given in Tab. II for the inconel and TZM core, where I_C , I_{Cb} and I_C^* are the critical currents in the short sample, in the curved conductor and under tensile load, and σ^* the tensile force at 8 T and I_C^* .

Tab. II: The critical currents of different conductor configurations at differ- ent stages of load at 8 T.	Core	I_c [A]	I_{cb} [A]	I_c^* [A]	σ^* [N/mm ²]
	Inconel T2M	2117 2383	1867 2050	2050 1675	141 115

The Tab. II reveals that the core materials inconel and T2M have a different effect on the current densities of Nb₃Sn under force load. Under the bending tension both conductor configurations experience a reduction in current density, the T2M configuration a little bit more than the inconel version. Under tensile forces the current density of the inconel version increases whereas that of the T2M version decreases. At the test the maximum load by running into the current sharing regime was 166 N/mm² with inconel and 137 N/mm² with T2M. These maximum loads were cycled five times and by that the T2M version exhibited an aging effect in the sense that from the first run to the fifth the I_c^* value dropped from 1800 A to 1675 A with a tendency of approaching a constant value. The conductors were stressed up to the plastic regime and a remaining strain of about 0.2 % could be measured by the change of conductor length. The behaviour of the T2M core conductor suggests a reduction of precompression effect by the small thermal contraction of molybdenum so that the original state is near the maximum value in the I_c/ϵ characteristic and the tensile forces lead very soon into the decreasing branch, as was verified by measurements of Specking et al.⁷⁾

Fig. 3: Stress-strain characteristic of the A 286 core conductor

A rewinding of the 5 m length of the inconel core conductor showed an enhancement of I_c^* up to 2133 A. That might be an effect of the plastic deformation reducing the precompression. A stress-strain characteristic of the A 286 core conductor is given in Fig. 3. The high content of copper and copper-tin bronze being in a weak state after the heat treatment leads to the very early indication of plastic behaviour at $\epsilon \geq 0.1$ %. At a virgin elongation of 0.3 % the conductor obtained a remaining elongation of 0.1 %. The stress strain behaviour at room temperature can be considered as representative also for LHe-temperature because the enhancement in yield strength and average modulus of elasticity at low temperature is negligible from a practical point of view.

CONCLUSION

The investigations have shown that strengthening considerably influences the critical current density of Nb₃Sn conductors, due to its differential thermal contraction coefficient. The results of the inconel respectively the A 286 core and of the T2M core suggest the possibility of compensating the thermal contraction effects by selected core materials. In the range of bending strain up to 0.6 % the prereacted conductor can be wound and rewound without any damage. The final bending strain should be small to keep the loss in critical current in a tolerable limit of 10 %.

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