INFLUENCE OF PRODUCTION PARAMETERS ON THE SUPERCONDUCTING PROPERTIES OF NBTI AND NB_3SN WIRES

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Abstract

The commercial specification of superconducting NbTi and Nb_3Sn composite wires is normally given by a few numbers : $I_c(\rho,B,T)$, n, RRR, wire and filament diameter and twist length. To some extent their values cannot be chosen independently, nor do they guarantee proper operation of the system in all aspects, for instance fields in dipoles for accelerators. For Nb_3Sn composites, depending on the production process, an extra set of parameters describing the stress sensitivity seems to be needed to specify the quality of the composite.

Introduction

The design aspects of some future superconducting machines like SSC, LHC and NET/ITER are not only based on the proven performance of available products but seem to challenge the wire and cable producers to improve the quality of their product.

Large improvements have already been obtained in the past eight years in the case of NbTi by changing the NbTi quality (higher homogeneity) as well as the wire design. Notable improvements are the required reduction of the filament diameter below 5 μm without the unwanted occurrence of sausaging of the filaments and reduction of low field proximity effects by additions to the matrix material. Nevertheless, it is difficult to translate the physical requirements of the system into a commercial specification to the wire manufacturer and the latter into a proper wire design and production process. Normally, a wire is commercially specified by a few parameters, only :

a) I_c in some field and temperature range;
b) an RRR value (or R_{300}/R_{10} value);
c) n value;
d) global geometrical layout parameters like wire diameter, filament diameter and filament distance as well as the twist length and direction.

It seems that these values are merely based on experience of what is possible, so the "best" product is obtained. For instance the n value specified for SSC wires is 30-35, but not much is known of the better performance, if, for instance, n=40 is required for the time dependence of higher harmonics of the dipole field. It is obvious that for another application, like MRI, the n value is a crucial parameter in so far the magnet operates at a total different level of effective resistivity than the wire is specified, $\rho = 10^{-20}$ Ωm vs. 10^{-14} Ωm.

More intriguing is the situation for Nb_3Sn. Here the same set of parameters is used as for NbTi, but due to the large difference in production processes, the reaction heat treatment, the mechanical properties of the final product and the higher fields of applications additional specifications seem necessary. Furthermore, it seems that the production method of the wires leads to products with different quality. Whether this is necessarily so is not systematically investigated, but some differences will be outlined below. These variations will add up in reducing the performance of the superconducting composite to those resulting from geometrical sources already present in NbTi, where larger uniformity in the results of the treatment can be achieved.

The n value as a quality parameter

The V-I relation of a superconducting composite in the neighbourhood of the critical current I_c,that is the current at which the effective resistivity is about 10^{-14} Ωm, can be described empirically by a power law

$$\frac{V}{V_0} = \left(\frac{I}{I_0} \right)^n . \qquad (1)$$

This n value is determined by measuring the V-I relation over one or two decades of voltage which corresponds to about 10 % in current. However, it has to be kept in mind that the n value is a function of I (or ρ_{eff}). This can be seen by redefining n as the slope on a log-log plot of the V-I characteristic at constant applied field and temperature, so

$$n = \frac{I}{V} \left(\frac{\partial V}{\partial I} \right)_{B,T} . \qquad (2)$$

Then, using the simple relation for the critical state

$$V = R(I - I_c) \ , \ I > I_c \qquad (3)$$

we obtain a hyperbolic increase of n(I) if $I > I_c$ and I approaches I_c :

$$n(I) = \frac{I}{(I - I_c)} . \qquad (4)$$

This increase towards lower I values is observable, but normally stops at n in the range 30-100 for "good" wires. The main reason for this may be threefold :

a) the imperfect geometry of the filaments;
b) the non-homogeneous distribution of the pinning along the length of the filaments;
c) the twist of the wire.

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By imperfect geometry of the filaments we consider, in first approximation, three major deviations from the ideal cylindrical shape :

1) the cross section is no longer a circular one;
2) short-term variations of the cross sectional area along the length of the filament or sausaging;
3) long term variations in the cross sectional area.

The influence of the second type of deviation is the most severe one, as was recognized in the mid 80's and was prohibitive for obtaining long lengths of wire of good thin filaments with diameter below 10 μm. About the influence of the unroundness of the filaments, but still having the same cross sectional area, not much is known. For the moment it is, however, believed to be of less importance, compared to the third deviation from ideality, where the current has to leave the filament if its cross sectional area decreases. Of course, this current sharing will take place at current values well below I_c since variations in the cross sectional area up to 80 % are no exception.

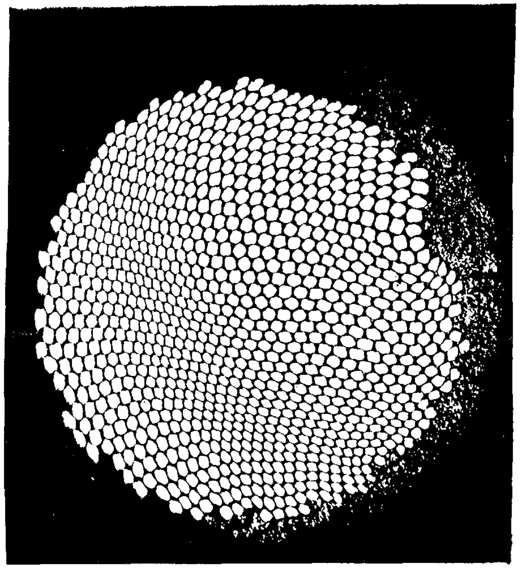

Fig.1 Photograph of a cross section of a wire showing the variations in the cross sectional area of the filaments.

The current sharing process is enhanced by the twisting of the wire. Due to the self field of the wire each filament will experience a variation of its external field with a period length approximately the twist length. Rough calculations have shown[1] that due to the consequent variations in the field the local current density at a voltage level of the order of 1 μV/m or an effective resistivity of 10^{-14} Ωm only a small percentage of the filaments is really saturated. Fig.2 shows the region in a wire with uniform filament distribution where the filaments are saturated. After resistivity onset, i.e. 1 μV/m full saturation will be obtained at much higher voltage levels, about 1 mV/m.

As a preliminary result it may also be mentioned that due to this geometrical effect of twisting combined with the self field n values are limited to 100-200 only. It is thought, that the observed further reduction is a consequence of the combined effect of twisting and long term variations of the intrinsic j_c value or the cross sectional area of the filaments.

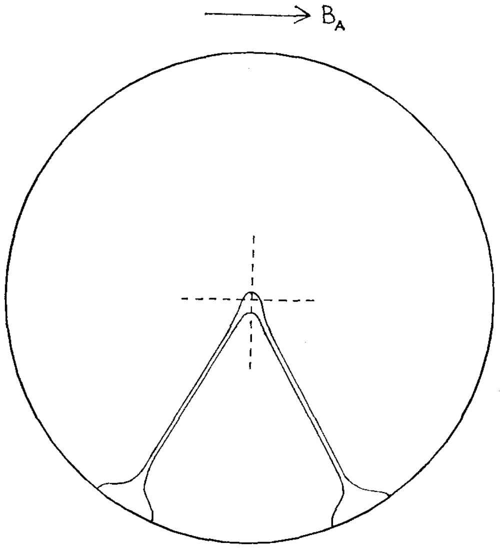

Fig.2 Schematic view of the cross section of a multifilamentary wire showing the region of saturation at the onset of resistivity. B_A denotes the applied field direction.

Both show up in the calculations in the same way, so no distinction can be made between them. Nevertheless, it is shown, that parameters like wire and filament diameter, twistlength and critical current at some field cannot be specified independently. Further improvement of n values can only be obtained by decreasing the variance of the filament size distribution. Although the foregoing is true for both NbTi and Nb_3Sn wires, in the latter some extra effects have to be considered.

Production methods for Nb_3Sn

In the past 30 years various production methods have been developed for the commercialization of Nb_3Sn composite wires. For our purpose it is convenient to distinguish between three groups depending on the composite layout before the reaction process. The main constituents of the wire are then, apart from barrier material and stabilizing copper :

1) Nb filaments (with Ti or Ta addenda) imbedded in bronze;
2) Nb, Cu and free Sn;
3) Nb tubes filled with Sn compounds ($NbSn_2$ or Nb_5Sn_6) or free Sn and optionally some Cu.

The resulting product then either contains Nb_3Sn imbedded in a low Sn bronze or Nb_3Sn surrounded by Nb. Since in the latter case the Nb acts as a barrier it can be directly imbedded in a stabilizing Cu matrix. The crucial part of the manufacturing process is the reaction heat treatment which in general is optimized for giving the highest I_c ($\rho = 10^{-14}$ Ωm). This means for the first two types of wire a complete conversion of all Nb into Nb_3Sn, whereas in the latter all Sn should be used.

Comparison of the j_c values obtained by the various methods is hampered by some lack of data in the literature. For a good comparison either the initial fraction of Nb or Sn used for the reaction is needed to calculate the final fraction of Nb_3Sn and so the intrinsic J_c of Nb_3Sn rather than the overall current density or the "non copper" current density. From the few data available and measurements it may be observed that wires and tapes (kindly put to our disposition by HORIZONT, Moscow USSR) reacted according to the last method i.e. using all Sn, have J_c values well above 3000 A/mm^2 at 10 T. Also n values well above 60 were measured both in this kind of Nb_3Sn tapes and wires. In bronze type wires, somewhat lower critical current densities are observed at some samples, although no general conclusions can be drawn. The n values of bronze wires were definitely lower, typically between 20 and 50.

So it seems that less current sharing is present in tube type wires. The larger filament diameter makes them presently, however, less suitable for accelerator magnets because of the resulting high level of higher harmonic fields. Also the application in fusion magnet systems is still under discussion because of the higher losses. Research programs have to be developed to overcome the drawbacks of the individual production methods since the potential of Nb_3Sn in this field of application is undoubted.

Stress dependence of Nb_3Sn

Another difference between Nb_3Sn and NbTi is its sensitivity for external forces, applied both longitudinally and transversely to the wire axis. Especially the latter effect has been studied in the last years. Again here only a few data exists in the open literature and a comparison is only preliminary. Also, like in the case of n values only an empirical description of the phenomena is possible and insufficient attention has been paid to the origin of the stress sensitivity. Rough calculations[2] on cylinders of a composite material, taking into account the elastic and plastic properties of the various materials indicate that large stresses are retained in the composite once it has been exposed to a transverse force which thereafter is taken away.

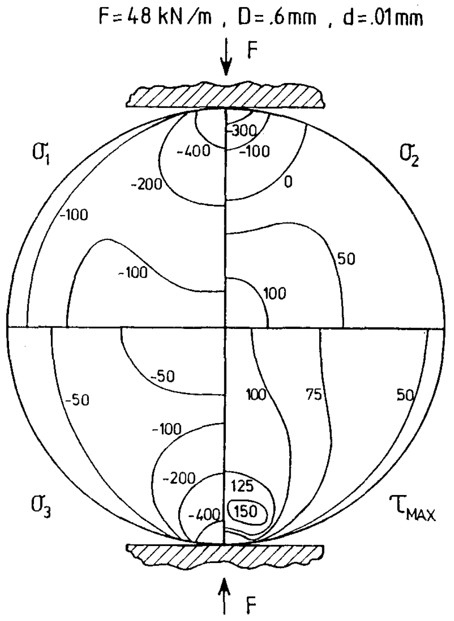

Fig.3 Stress pattern in a wire. Shown are the three principal stresses ($\sigma_3 = \sigma_z$) and maximum shear stress τ_{max} in Mpa.

In fig.3 the main components of the stress tensor are shown after releasing the transverse force to the cylinder.

This leads to hysteresis effects in the I_c vs. external strain curves. Since these effects are governed by the internal structure of the composite, a different behaviour is expected for different layout of the wire. This is illustrated for a bronze wire and a tube wire in fig.4 by plotting $I_c^{1/2}$ vs. B_A.

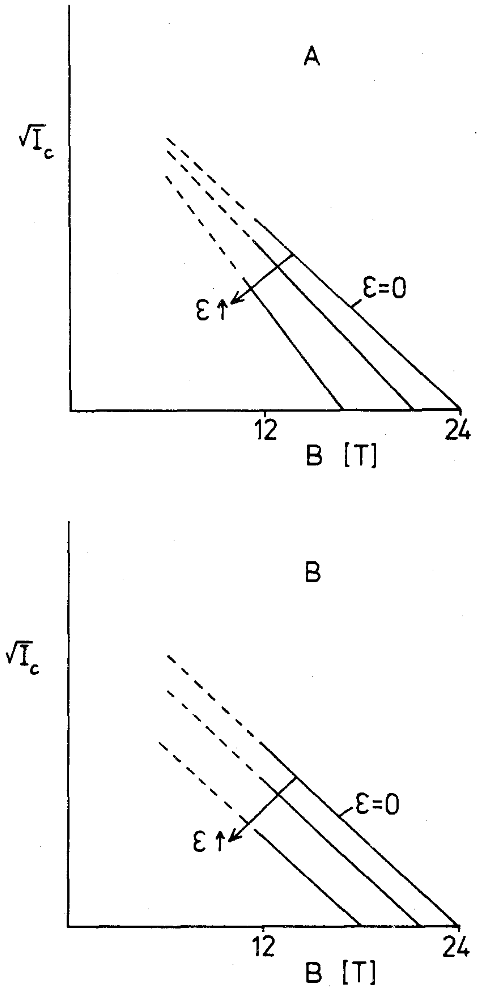

Fig.4 Typical $\sqrt{I_c}$ vs. B curves for various values of longitudinal strain ε. A : bronze wire, B : tube method wire.

The upper curves correspond to the situation where "the prestress is compensated". Giving also the maximum value of $B_{c2}(\varepsilon)$ it may be noted that in the case of the bronze wire not only $B_{c2}(\varepsilon)$ decreases if ε increases, but also the slope of the curves increase, in contradiction to the tube wire where almost no prestress is present and the curves shift parallel to the stress free one.

A more pronounced effect occurs when transverse force is applied to the wire. In fig.5 typical V-I relations[3] of bronze wire are shown , taken under various values of transverse force. From this figure it may be noted that applying a force not only decreases the $I_c(\rho)$ value, but also changes the slope of the V-I curve, n=25 for the uncompressed wire. At higher values of ρ an increase of n by a factor 2-3 up to 80 is observed whereas at low ρ values a decrease of n with the factor 4 down to 7 occurs. Also after releasing the force no complete recovery of the original state is obtained (hysteresis).

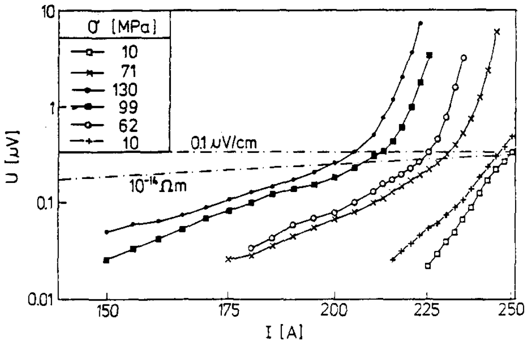

Fig.5 Voltage-current characteristics at 7.0 T for different stress levels during one load cycle.

This example just shows the presence of the transverse stress sensitivity of the wire. The observed magnitude of the effect may depend on the measuring method as well as on the production method of the wire. On the other hand it shows that specifying a n value of a wire without characterizing its prestress state does not predict the final performance of the system. Large deviations may already occur by cabling these wires[4].

Conclusions

With some precaution it may be said that differences exist between the physical characterization of superconducting composites and commercial specifications. The latter are not always independent nor do they guarantee the performance of the system as expected by the designer. The stress sensitivity of Nb_3Sn can enhance the difference between specified and actual performance. New ways and measuring methods have to be found and defined to close this gap. Moreover, the large variety in production methods and the way results are presented make intercomparison difficult, so preventing a better interpretation of the results and a possible upgrading of the quality of Nb_3Sn.

References

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