THE INFLUENCE OF TRANSVERSE, COMPRESSIVE STRESS ON THE CRITICAL CURRENT OF MULTIFILAMENTARY Nb_3Sn AND NbTi WIRES.

H. Boschman, P.P.E. Fornerod and L.J.M. van de Klundert.

University of Twente, Applied Superconductivity Centre,
P.O.Box 217, 7500 AE Enschede, The Netherlands.

Abstract

In order to investigate the critical current of multifilamentary wires as a function of the applied field and transverse, compressive stress, a special experimental arrangement has been developed. In this arrangement, the repulsive Lorentz force generated by a set of magnets is used, to press a sample between two parallel surfaces. From the first experimental results on a multifilamentary NbTi wire, it is concluded that the arrangement functions properly.

Introduction

The effects of axial stress and strain on the current-carrying capacity of multifilamentary NbTi and Nb_3Sn wires have been studied extensively during the past.[1-3] For the design of magnets, it is important to know the stress-dependence of the critical current, because axial stress occurs on the windings due to Lorentz force. Especially in the case of large scale magnets, the axial stress can become very high (the stress is proportional to the radius).

For NbTi conductors, it has been found that degradation of the critical current occurs, as soon as they are strained. This effect is reversible to a large extent: as soon as the mechanical load on the conductor is released, the original critical current is almost completely restored. At fields below 7 T, a degradation of 5 % can be observed, if the conductor is strained more than 1 %. The latter value corresponds to a stress of approximately 0.5 GPa, a number which is usually not achieved in small-scale magnets. Therefore, the influence of axial stress is commonly not a serious problem in magnet design with NbTi wires. In the case of Nb_3Sn conductors, however, the effects of axial strain are qualitatively the same, but occur at much lower strain values. In the case of NbTi conductors, fractures occur only when the strain is over 4 %, whereas tensile strains ranging from 0.1 to 0.3 % may already be sufficient to damage Nb_3Sn filaments, resulting in permanent lower maximum currents. If compressive pre-strain is present in a Nb_3Sn conductor, it can be strained to a larger extent before irreversible effects occur, but the maximum is hardly more than 1 %.

Transverse stress also occurs in magnets due to the Lorentz force, but resulting degradation effects on the critical current had not yet been studied until recently. Research on this issue during the last two years shows that transverse stress causes an even larger degradation of the critical current of Nb_3Sn conductors than axial stress does.[4-6] Because the increase of transverse stress is proportional to the thickness of the conductor in the direction perpendicular to the field and current (i.e. in radial direction for solenoids), effects of degradation can be expected, when superconducting composites with large dimensions are used. In the case of cabled superconductors, large local stresses occur at the cross-over points, which can aggravate the degradation effect.

In this paper, a special experimental arrangement is described, which has been developed for the investigation of the critical current of multifilamentary wires as a function of applied magnetic field and transverse, compressive stress. The first results on a multifilamentary NbTi wire are presented.

Experimental set-up

During the measurements of the voltage-current characteristics, the wire under investigation is pressed between two parallel pressure surfaces. The force needed to press the surfaces onto each other is delivered by the repulsive Lorentz force of a special, superconducting coil system that is placed above the field magnet. In this way, it is not necessary to generate the force at room temperature and transmit it into the cryostat by means of a rod.

Figure 1 shows the press-arrangement, of which all parts are made of stainless steel. On the two pressure surfaces, there is a 0.5 mm thick layer of chromium to harden them. The lower pressure surface is attached to the field magnet (not shown in the figure) and therefore, they can be considered to form a mechanically fixed structure, together with the bar and the nut. The other parts of the arrangement, however, can be moved along the bar with hardly any friction. This movement is restricted to the limited space between the lower pressure surface, on which the wire has been laid, and the nut, which has been turned onto the bar without using force. As a result, when the set of coils is activated, the ring and upper coil are pressed against the nut, while the lower coil and the part with the upper pressure surface are pushed downward. In this way, the wire, which has been reacted and laid between the pressure surfaces in a spiral shape, experiences a transverse, compressive stress. Current is supplied to the sample by means of two soldered joints, that lie in grooves on the in- and outside of the movable part of the apparatus. Thin voltage taps are soldered to the side of the wire and are laid spirally next to the wire. In this configuration, sample lengths of 60 cm can be easily realised.

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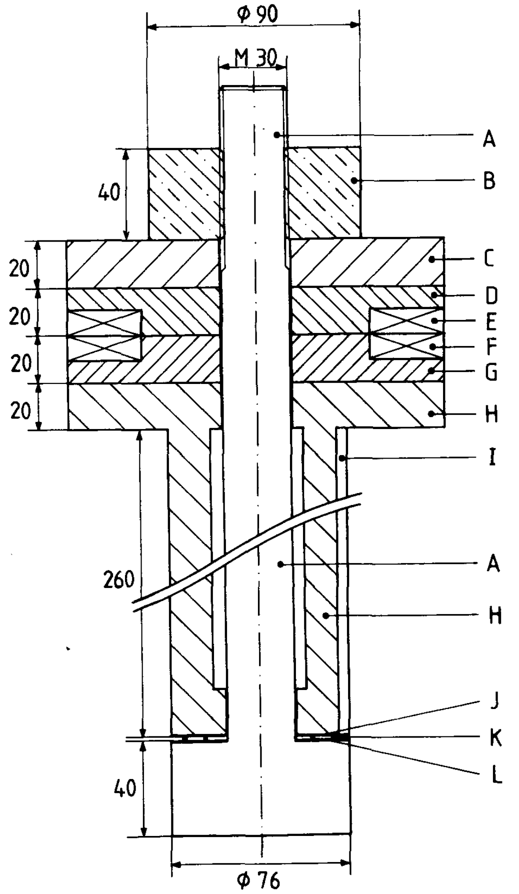

A: Bar
B: Nut
C: Ring
D: Upper coil holder
E: Upper coil (1)
F: Lower coil (2)
G: Lower coil holder
H: Spacer between sample and set of coils
I: Groove for joint
J: Upper pressure surface
K: Spirally-wound sample
L: Lower pressure surface

Figure 1: Cross-section of press-arrangement. Sizes in millimetres.

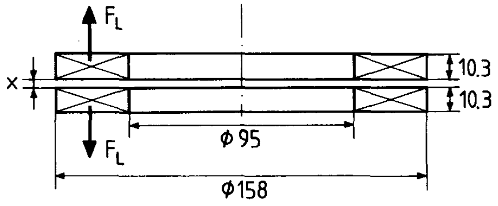

Figure 2: Cross-section of the coil system. Sizes in millimetres.

Forces caused by the coil system

If the direction of the current in two coaxially aligned coils (figure 2) is opposite, they repel each other due to the Lorentz force[7]. The energy of such a set of coils is given by:

$$W_{set} = \frac{1}{2} L_1 I_1^2 + \frac{1}{2} L_2 I_2^2 - M I_1 I_2 , \qquad (1)$$

in which L_1 is the inductance of a single coil, I_1 the current and the indices 1 and 2 refer to the upper and lower coil respectively. M is the mutual inductance between both coils and can also be written as: $M = k \sqrt{(L_1 L_2)}$, in which k is the coupling coefficient. Note, that in equation (1) only M is a function of the distance x between the coils. The repulsive Lorentz force can be found by differentiation of equation (1):

$$F_L(x_0) = \left.\frac{\partial W_{set}}{\partial x}\right|_{x=x_0} = - I_1 I_2 \left.\frac{\partial M}{\partial x}\right|_{x=x_0} , \qquad (2)$$

in which x_0 is the operating distance. If both coils and their currents are identical ($L_1=L_2=L$ and $I_1=I_2=I$), equation (2) reduces to:

$$F_L(x_0) = -I^2 \left.\frac{\partial M}{\partial x}\right|_{x=x_0} = - L I^2 \left.\frac{\partial k}{\partial x}\right|_{x=x_0} . \qquad (3)$$

Because the term $\frac{\partial k}{\partial x}$ is optimal for x=0, the operating distance between the coils must be low, in order to achieve a high repulsive force. Also, the height of the coils must be limited, because, in that case, the influence of small variations in x lead to large differences in the coupling coefficient. The optimum in the term LI^2 is determined by the critical current of the superconducting wire in relation to the maximum field in the coil configuration.

On basis of the above-mentioned considerations, a set of coils has been realised, between which the maximum Lorentz force according to equation (3) is approximately 130 kN. However, for the calculation of the total force on the sample F_{sample}, two additional effects must be taken into account. Firstly, because the coils are operated in the vicinity of a large field magnet, the influence of its current I_A must be considered. The lower coil of the system experiences an additional force due to the magnet and can be written as: $\pm I_A I_2 \left.\frac{\partial M_2}{\partial x}\right|_{x=x_A}$, in which x_A is the distance between the middle of the field magnet (where the sample lies) and the midplane of the set of coils and M_2 is the mutual inductance between the magnet and the lower coil. The minus-sign is valid (i.e. the force is directed downward), if I_A and I_2 are in the same direction. Note, that the magnet current also influences the upper coil of the system, but during operation this coil is pushed against the nut, which is fixed to the field magnet. Therefore, this additional force does not contribute to F_{sample}.

Secondly, attention must be paid to the mass of the sample holder. When the system is not operated, the weight of the movable parts (18.1 kg) rests on the wire. However, during operation the upper coil is lifted up and eventually pressed against the nut. As a consequence, only the lower movable parts (12.3 kg, which is approximately 120 N) press on the sample and in that case, the force exerted on the sample can be written as:

Table 1: Data of the coil system.

Conductor:

Manufacturer:	Vacuumschmelze
Number of filaments:	54
Diameter of insulated wire:	0.33 mm.
Cu/NbTi-ratio:	1.35

Single coil:

Number of turns:	2492
Inductance L_1 and L_2:	0.997 H.
Resin (wet wound):	Stycast 2850 FT/LV24

Coil system:

Operating distance between coils x_0:	0.3 mm.
Mutual inductance M:	0.775 H.
Max. operating current I_{max}:	67 A.
Repulsive Lorentz force at x_0 and I_{max}:	130 kN.
Inductance system L_{sys}:	0.444 H.
$\partial M/\partial x$ at x_0:	-26.6 H/m.

Inductances coil system with field magnet:

Field factor of magnet:	0.137 T/A.
Distance between midplane field magnet and coils x_A:	0.300 m.
M_1 at x_A:	0.187 H.
M_2 at x_A:	0.210 H.
$\partial M_1/\partial x$ at x_A:	-2.01 H/m.
$\partial M_2/\partial x$ at x_A:	-2.35 H/m.

Table 2: Characteristics of investigated wire.

Manufacturer:	MCA
Number of filaments	2070
Diameter of wire:	0.686 mm.
Cu/NbTi-ratio:	1.8
Sample length:	63 cm.

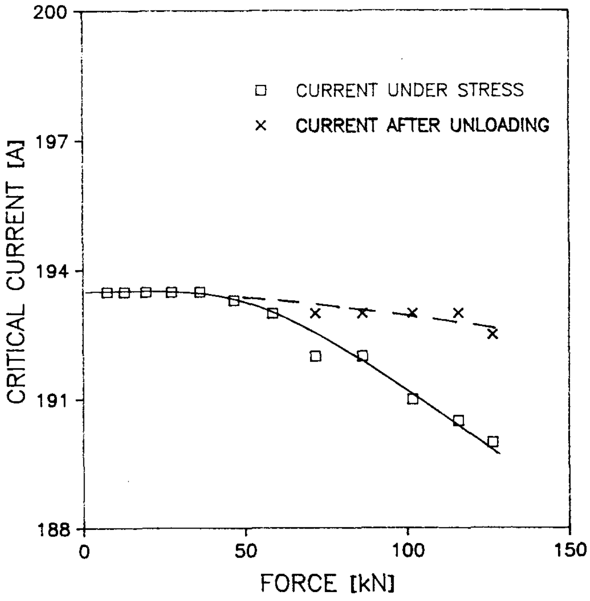

Figure 3: Critical current of investigated wire under transverse stress. Applied field: 6.0 T.

$$F_{sample} = -I^2 \left.\frac{\partial M}{\partial x}\right|_{x=x_0} \pm I\, I_A \left.\frac{\partial M_2}{\partial x}\right|_{x=x_A} + 120. \tag{4}$$

It should be noted, that the influence of the mass is relatively small at high currents. For example, at I = 10 A it contributes for approximately 4 % of the total force, whereas it diminishes to less than 1 % at currents over 20 A.

Table 1 and figure 2 give the data of the realised coil system. From these data and equation (4) the force on the sample can be calculated with an accuracy of approximately 1 %. This accuracy is mainly limited by the rapid change in $\partial M/\partial x$ with respect to variations in x_0. The error is relatively small, however, when the compressive stress is calculated from F_{sample} and geometrical factors of the wire such as length and diameter. In the case of round wires in particular, crude assumptions have to be made about the stress distribution across the wire. This will be discussed later on.

The field pattern due to the coil system alone has a sharply peaked maximum in the plane between the two coils. The field magnet, however, changes both the place and the value of the maximum. As a consequence, the maximum current is dependent on the applied field on the sample. It has turned out, that the set of coils can be safely operated up to 67 A at all fields. The influence of the field of the coil system on the sample is negligibly small: i.e. less than 1.5 mT.

First experimental results

In order to illustrate the performance of the press-arrangement, the critical current of a multifilamentary NbTi wire under transverse stress was investigated. The characteristics of the wire are shown in table 2. Figure 3 shows the results of the critical current measurements, that were carried out at a field of 6.0 T. Although a large force of approximately 130 kN was exerted on the wire, only small reductions of the current carrying capacity were observed: less than 2 %. The critical current recovers almost to its original level after unloading the sample. Figure 4 shows the cross-section of the wire after the experiments. It can be seen that the contact area between the pressure surface and the originally round wire has increased. This means that a permanent deformation of the materials, especially of the copper, has taken place. A result of this change in shape may be a permanent stress that is exerted on (parts of) the filaments, which can explain the fact that the recovery is not complete after unloading.

One of the main problems of these kinds of experiments is how the internal stress on the superconducting material can be evaluated from the force that is exerted on the outside of the round, composite wires. As can be seen in figure 4, the wire is deformed as a result of the load. This leads to another stress-pattern inside the wire. It can be imagined that the transverse, compressive stress on a filament is dependent on the size of the contact area and the position of the filament inside the wire. Because material is pushed sideways, some filaments may even be exposed to tensile stress. Note that the problem of internal stress distribution is not unique for the developed press-arrangement, but plays also an important role in magnets. The analysis of this mechanical problem is the scope of future investigations.

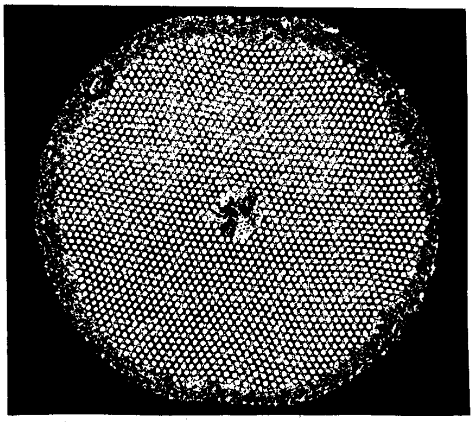

Figure 4: Cross-section of investigated wire after experiments.

Conclusions

The first measurements have shown that the press-arrangement functions properly. A compressive force on the wire can be easily applied by regulating the current through the set of coils. Another result of the experiment is that the critical current of a multifilamentary NbTi wire is diminished under influence of a transverse force. Note that larger stresses in the wire and presumably larger degradation effects could have been achieved by chosing a smaller sample length. Larger effects of transverse stress are expected on wires with Nb_3Sn, which will be investigated in the near future. Another interesting issue will be the stress-distribution in a multifilamentary wire due to a transverse force.

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