AC LOSSES IN ULTRA-FINE FILAMENT NbTi SUPERCONDUCTORS

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Abstract

Loss measurements are presented on an ultra-fine filament composite and on a regular AC conductor, having "thick" filaments. The wires have been subjected to an alternating transverse magnetic field. An AC as well as a DC transport current have been fed through the wires. The magnetic field and the AC transport current have been sinusoidal functions in phase. The magnetization losses and the transport current losses have been measured separately. The critical current - according to the 10^{-14} Ωm criterium - and the quality factor n - according to $V = V_0(I/I_C)^n$ - have been determined.

Introduction

In the last few years progress has been made on the manufacturing processes of multifilamentary superconducting wires. In order to reduce the losses of the conductors under AC conditions much effort has been put in the reduction of the filament diameter and the twist pitch to wire diameter ratio. As a result multifilamentary conductors with filament diameters below the 1 micron range can now be produced on an industrial scale. Dubois et al. [1] have already reported a twist pitch to wire diameter ratio down to 4 with a minor current decrease. The reduction of the filament diameter and the twist pitch combined with the use of high resistance matrix material - like Cu30Ni - has led to an essential reduction of the AC losses. However, for the use of fine-filament conductors in industrial applications, a thorough knowledge of the AC losses as well as the critical currents and the stability is required.

The test set-up

The magnetic field

The test set-up has been designed in order to study the loss behaviour of a test wire, subjected to an alternating transverse magnetic field superimposed on a background field. The AC and DC coil are energized using separate power supplies. The AC magnetic field power supply is an AMCRON M-600 power amplifier which is controlled by an LSI-11 computer system. As AC coil an outer-notch solenoid, made of a 0.200 mm NbTi/CuNi conductor having 574 filaments, has been used. The inner and outer radius are resp. 9 mm and 13 mm. The length of the coil is 45 mm. The inductance of the coil is 24 mH. The magnetic field is homogeneous within 1% in the test volume.

The transport current

The test wire has been wound non-inductively on a bobbin in order to minimize the coupling between the test sample and the AC coil as well as to minimize the magnetic induction due to the transport current. The remaining coupling effect has been suppressed by putting a resistance in series with the sample coil. The cryostat has been provided with current leads in order to feed the test wire with a transport current.

The signal processing

The magnetization losses - hysteresis losses in the filaments and coupling losses in the matrix material - and the transport current losses can be determined separately. The magnetization losses have been measured by means of a set of pick-up coils. The voltage drop along the test wire has been measured using voltage taps. Therefore the transport current losses could be determined. Several compensation techniques have been included in order to enhance the accuracy. The major part of the inductive component of the pick-up voltage is compensated in the cryostat by means of a compensation coil. The final compensation is achieved by using a toroid in series with the AC coil. The loss voltage along the wire is also compensated for an inductive component. The pick-up voltage is subtracted in order to compensate for the demagnetization field [6]. Compensation for the demagnetization field is important in the case of small transport currents and large magnetic field amplitudes. A set of low noise differential amplifiers is used for compensation, amplification and filtering of the signals. The final signal processing is performed by the computer system, which includes averaging and numerical integration.

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Data of the wires

Two wires have been tested. Cross-sections of both wires are shown in Fig. 1. The data of the wires are listed in Tab.1.

Table 1. Characteristics of the test wires.

manufacturer	Alsthom	MCA
wire diameter	0.120 mm	0.127 mm
number of filaments	14496	114
filament diameter	0.58 μm	7.8 μm
ratio Cu:CuNi: superconductor	0.83:1.16:1	0:1.35:1
matrix	Cu/CuNi	CuNi
twist pitch	0.8 mm	10 mm

Theories

The experimental results have been compared with several models which describe the loss behaviour of multifilamentary wires with a poorly conducting matrix.

Pang [4] calculated numerically the hysteresis losses in a superconducting cylinder. For applied fields $\hat{B_a}$ larger than the penetration field B_p the numerical results were found to be within 10% of the following analytical expression:

$$Q_h = 4\,\mu_0\,\hat{B_a}\,B_p(2-B_p/\hat{B_a})/3 \quad [\mathrm{J/m^3}] \qquad (1)$$

with $B_p = \mu_0\,J_c\,d/\pi$.

This formula can be extended to a multifilamentary wire, if the screening effect, due to the coupling currents, and the proximity effect can be neglected, to

$$Q_h = \pi\,d^2\,N\,\mu_0\,\hat{B_a}\,B_p(2 - B_p/\hat{B_a})/3 \qquad [\mathrm{J/m}], \quad (2)$$

with N is the number of filaments, d is the filament diameter and J_c is the critical current density.

Carr [7] derived an expression for the coupling losses in the case that no saturation has taken place. The coupling current losses for sinusoidal alternating transverse magnetic fields, having a frequency $f \ll 1/\tau$ (τ is the time constant of the wire), is given by:

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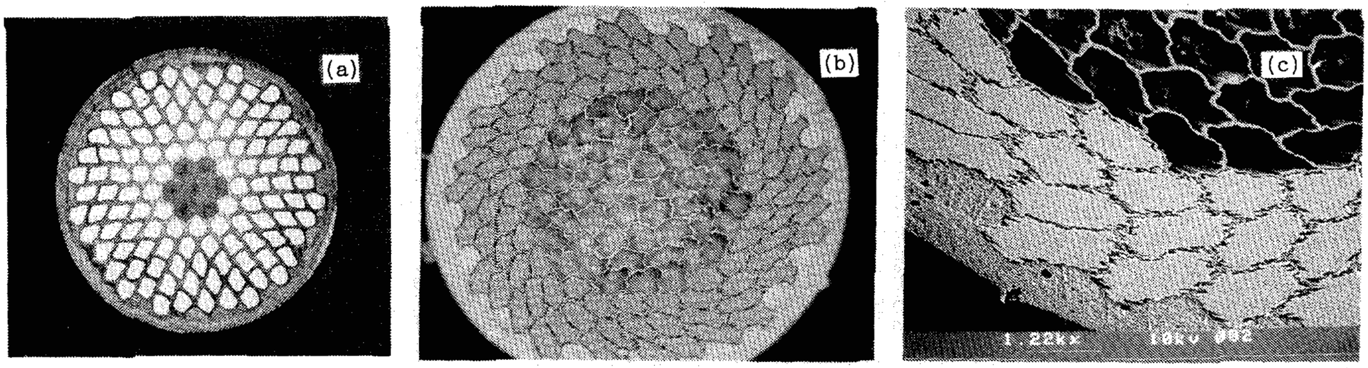

Figure 1. - Cross-sections of the MCA wire (a) and the Alsthom wire (b and c).

$$Q_c = \pi D^2 f \hat{B}_a^{2} L_p^2 \sigma /8 \qquad [J/m], \quad (3)$$

with D is the wire diameter, L_p is the twist pitch, and σ is the transverse conductivity.

Ogasawara et al. [3] investigated the effect of a DC transport current on the hysteresis losses in a single core conductor. Using a slab model he derived expressions for the magnetization losses Q_m and for the transport current losses Q_i. Adjusting these expressions for a multifilamentary wire yields:

$$Q_m = \frac{\pi}{8} \mu_0 I_c d\left[(1 - i^2) \frac{2 \hat{B}_a}{\mu_0} - \frac{2}{3} \frac{I_c}{Nd} (1 - 3 i^2 + 2 i^3)\right] \qquad [J/m] \quad (4)$$

$$Q_i = \frac{\pi}{4} \mu_0 I_c d\left[i^2 \frac{2 \hat{B}_a}{\mu_0} - \frac{I_c}{Nd} i^2 (1 - i)\right] \qquad [J/m], \quad (5)$$

with $i = I_{dc}/I_c$, I_c is the critical current and I_{dc} is the transport current.

De Reuver et al. [6] calculated and measured the effect of an AC transport current on the magnetization losses and the transport current losses. Rem [5] calculated numerically and analytically Q_m and Q_i. In the unsaturated case the losses are expressed analytically as:

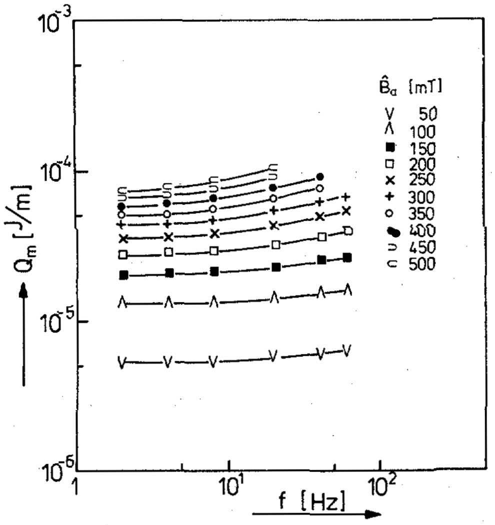

Figure 2. - Magnetization losses per cycle per unit of length in the MCA wire as a function of the frequency for different applied magnetic field amplitudes.

$$Q_i = -\frac{32}{\pi^5} \mu_0 I_c^2 \hat{i}\sqrt{\pi b} \sum_{k=0}^{\infty} (2k+1)^{-7/2} F\left(\sqrt{\frac{(2k+1)\pi}{2b}}\right) \quad [J/m] \qquad (6)$$

$$Q_m = \frac{16}{3\pi^2} \mu_0 I_c^2 \left(4b - \frac{\pi Q_i}{\mu_0 I_c^2}\right) \qquad [J/m] \quad (7)$$

with $b = \dfrac{\pi^2 d \hat{B}_a}{2 \mu_0 I_c}$, $\hat{i} = \dfrac{\hat{I}_{ac}}{I_c}$ and

$$F = \frac{ber_0\, ber_1 - ber_0\, bei_1 + ber_1\, bei_0 + bei_0\, bei_1}{ber_1^2 + bei_1^2}$$

The MCA wire

Fig. 2 shows the result of the measurements of the magnetization losses on the MCA wire as a function of the frequency of the applied field. The losses have been measured without a transport current. The slight frequency dependence indicates that the hysteresis losses in the filaments and the coupling current losses are of the same order of magnitude. The results have been fit with a first order polynominal using a least

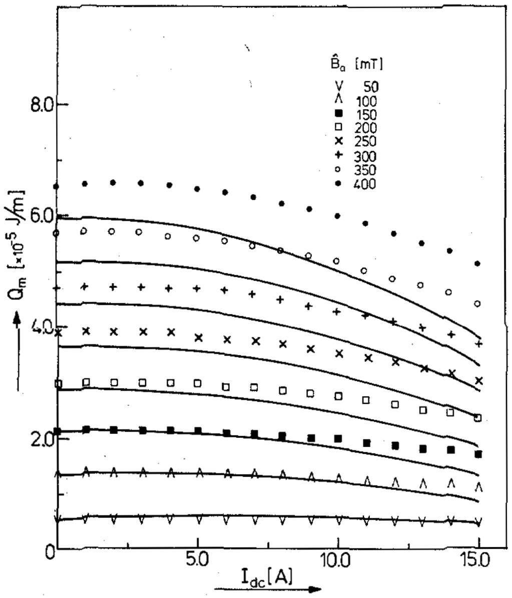

Figure 3. - Magnetization losses per cycle per unit of length in the MCA wire as a function of the DC transport current for different magnetic field amplitudes at 8 Hz.

square fit method. The coefficients of the polynominal combined with Eq. 2 and 3 yield the critical current density and the effective transverse conductivity. Using this method J_C and σ were found to be resp. $4\ 10^9$ A/m^2 and $1\ 10^7$ $(\Omega m)^{-1}$. Direct measurement of the critical current density yields $4.7\ 10^9$ A/m^2. The conductivity of Cu30Ni is $2.75\ 10^6$ $(\Omega m)^{-1}$. The presence of superconducting filaments however enhances the effective transverse conductivity if the surface resistance between the filaments and the matrix is sufficiently low.

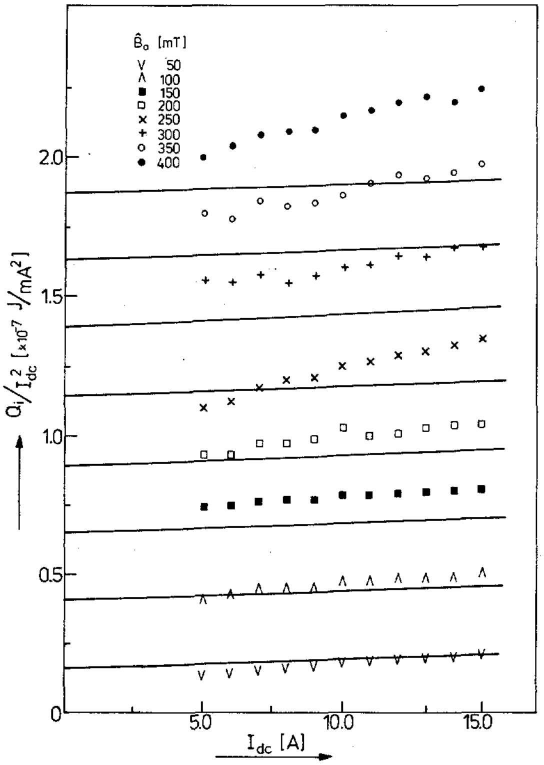

Figure 4. - Scaled transport current losses per cycle per unit of length in the MCA wire as a function of the DC transport current for different magnetic field amplitudes at 8 Hz.

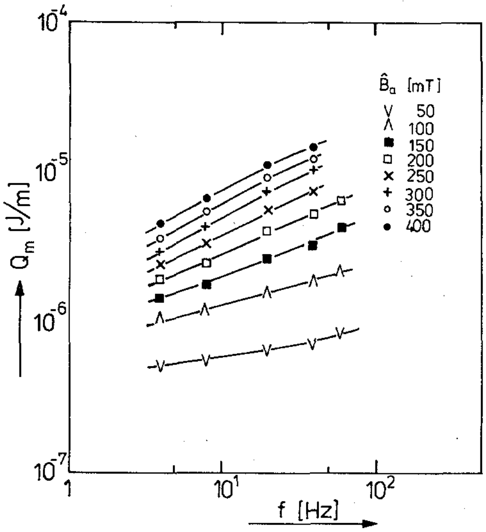

Figure 5. - Magnetization losses per cycle per unit of length in the Alsthom wire as a function of the frequency for different applied magnetic field amplitudes.

Fig. 3 shows the magnetization losses as a function of the DC transport current at 8 Hz. The solid lines represent the predicted losses calculated by Ogasawara et al. [3] in the case that the coupling current losses play an inferior role. Fig. 4 shows the transport current losses scaled by the square of the transport current as a function of the transport current at 8 Hz. The solid lines correspond with the loss calculations performed by Ogasawara et al. [3]. The measurements have also been performed at 40 Hz. The magnetization losses as well as the transport current losses show the same kind of behaviour as the losses at 8 Hz, although both magnetization losses and transport current losses are about 60% larger at 40 Hz than at 8 Hz.

The magnetization losses and the transport current losses in case the wire is carrying an AC transport current is well described by Eq. 6 and 7. The transport current loss measurements as well as the magnetization loss measurements at 8 Hz agree within 20% with the theory.

The critical current, according to the 10^{-14} Ωm criterium, at a 2 Tesla background field has been found to be 27 A. The quality factor n $(V = V_0(I/I_C)^n$ has been determined to be approximately 50 in the 4 to 6 Tesla background field range. n could not be determined at lower fields.

The Alsthom wire

Fig. 5 shows the magnetization losses of the Alsthom wire, not carrying a transport current. The losses are presented as function of the frequency for different field amplitudes. The same fitting procedure as mentioned above results in a critical current density of approximately $5.5\ 10^9$ A/m^2 and an effective transverse conductivity of $4.5\ 10^8$ $(\Omega m)^{-1}$. The critical current density (10^{-14} Ωm-criterium) at 2 Tesla background field has been found to be $2.3\ 10^9$ A/m^2. The measured hysteresis losses in the filaments are therefore more than 2 times larger than is expected from Eq. 1. This has also been found by Dubots et al. [2]. According to Hlasnik and Takacs [8] this is mainly due to the proximity effect, which implies a larger effective filament diameter. The effective transverse conductivity is enlarged by the copper in the central core by at least a factor 10.

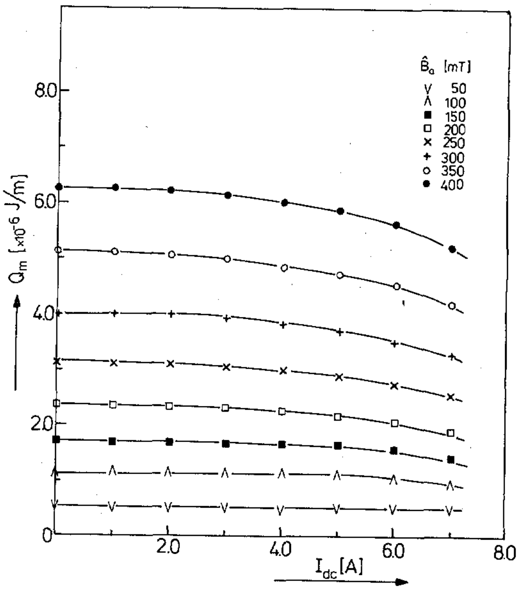

Figure 6. - Magnetization losses per cycle per unit of length in the Alsthom wire as a function of the DC transport current for different magnetic field amplitudes at 8 Hz.

Fig. 6 shows the magnetization losses in the Alsthom wire at 8 Hz as a function of a DC transport current. The magnetization losses decrease for increasing transport current as is expected. Fig. 7 shows the scaled transport current losses at 8 Hz as a function of a DC transport current. The losses tend to the losses predicted by Ogasawara [3] for transport currents smaller than 3 Amps. For larger transport currents however the increase of the current losses is larger than expected. It is not easy to ascribe this effect to saturation of the filaments considering the time constant of the wire, which is approximately 5 µs.

Fig. 8 shows the the scaled transport current losses as a function of an AC transport current at 8 Hz. Critical current measurements in the range of 0 to 2 Tesla have indicated an n-value of approximately 30.

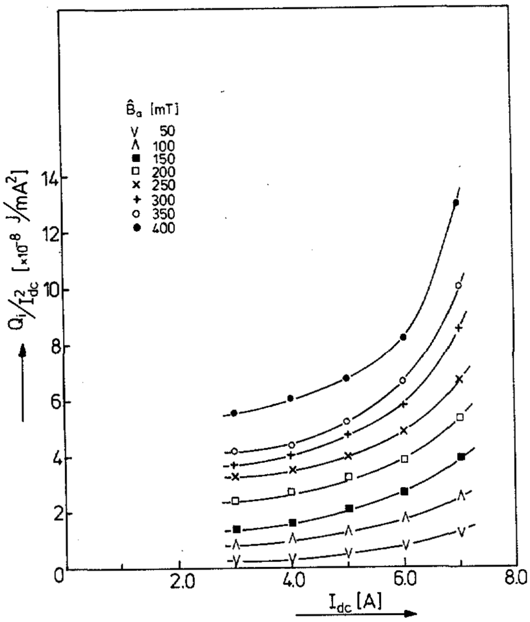

Figure 7. - Scaled transport current losses per cycle per unit of length in the Alsthom wire as a function of the DC transport current for different magnetic field amplitudes at 8 Hz.

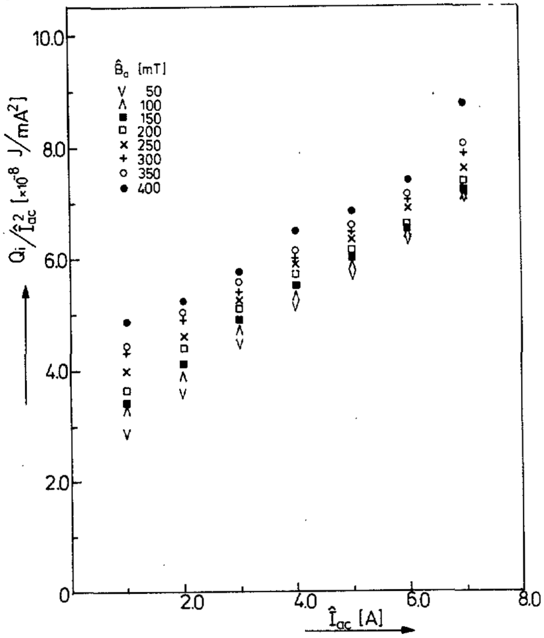

Figure 8. - Scaled transport current losses per cycle per unit of length in the Alsthom wire as a function of the AC transport current for different magnetic field amplitudes at 8 Hz.

Conclusions

The overall losses per unit of volume of the Alsthom wire are approximately a factor 10 lower than the losses of the MCA wire. Considering the contribution of the coupling current losses to the total losses and the percentage of copper in the central core an essential reduction of the losses can be established if the matrix would consist merely of CuNi. Replacing the copper by CuNi is of course only useful if the stability requirements are still fulfilled. It is very doubtful whether a further reduction of the filament diameter will lead to a substantial reduction of the hysteresis losses in the filaments.

The transport current losses show a peculiar behaviour. The question arises whether this is due to damage of the filaments - this would also explain the low value of n - or this is inherent in the fine-filament structure. The cross-section of the Alsthom wire however shows a distortion of the wire.

The critical current density of the Alsthom wire at a 2 Tesla background field is lower than what is commonly achieved nowadays. The critical current density at zero background field of the Alsthom wire however is larger than of the MCA wire. Research on the improvement of the critical current of the Alsthom wire at higher fields has already been reported.

These preliminary results of loss measurements and critical current measurements on the Alsthom wire and the MCA wire show an important improvement in AC conductor technology. The measurements are not performed in order to verify specifications of both wires, given by the manufacturers, but rather to show the effect of the reduction of the filament diameter.

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