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CRITICAL CURRENT AND STABILITY EFFECTS BETWEEN 0 AND 6 TESLA IN MONO AND MULTIFILAMENTARY NbTi CONDUCTORS HAVING A CuNi MATRIX*

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Abstract

We investigated the current carrying capacities of ten NbTi superconductors having a CuNi matrix with diameters between 50 and 300 μm as function of an applied magnetic field of 0 to 6 tesla. The effects of the method of wire fixation and the electrical connections were studied. The results are compared to those obtained with two common conductors with Cu matrix. We observed large differences of a factor 2 between the critical current densities of the various CuNi matrix conductors. Furthermore, it is remarkable that the best CuNi matrix conductors have critical current densities which are much higher than those in Cu matrix conductors.

Introduction

The technology of NbTi superconductors having copper-nickel matrices is essential for the development of thermally controlled superconducting switches[1]. Furthermore these conductors find application in the windings of superconducting a.c. transformers and a.c. switching coils for magnetically controlled switches[2]. However, in each type of application the CuNi matrix has a different function. In switches, the CuNi matrix determines the longitudinal resistivity of the wire and thus the off-resistance of the switch, while in a.c. coils the essential property of the CuNi is to increase the transverse resistivity in order to reduce eddy current loss. Nevertheless for all purposes the suitability of the various NbTi-CuNi wires will be mainly decided by their critical current density J_c which is determined by the NbTi alloy composition as well as by the final microstructure in the superconducting wire. The microstructure that shows a large J_c is obtained during the wire production by cold work effected by wire drawing and a number of heat treatments. The dominating effects that cause flux-line pinning and thus a high J_c are a high dislocation (cold work) as well as the presence of α-Ti precipitations (heat treatment). As a consequence of this, large differences between J_c values of various commercial superconductors can be expected. Therefore, it remains important to measure the critical current density of sc. wires.

A second important argument for J_c measurements is that calculations of a.c. losses in single sc. wires and magnets requires precise knowledge of the $J_c(B)$ behaviour. A comparison of measured and calculated a.c. losses is often handicapped by this lack of information about J_c especially at low magnetic fields.

This activity is part of our present program for the development of superconducting rectifiers including transformers and switches for large currents and power[1].

Samples and test method

Ten NbTi wires having a CuNi matrix were studied together with two wires having a Cu matrix. Their main physical data are collected in Table I. The 574 filament conductors W_4-W_6 have been manufactured especially for our rectifier project. The others are existing commercial products. The internal arrangements of the filaments in the various conductors are shown in figures 1a-g.

The test samples were mounted in a hairpin geometry (radius 25 mm) on a holder made of glass-fibre epoxy plate and inserted in a 6 T split-coil magnet, see figure 2. The method of wire fixation will be discussed later. The conductor was soldered to the terminals with a junction length of 15 cm which is sufficiently long to prevent current degradation as result of the properties of the joint. The joints are located outside the high-field region. The voltage to detect J_c was sensed over a length of 8 cm. The maximum currents are measured by using a ramp current with a low current rate ($\dot{I} < 1$ A/s). The critical current density is determined by the criterion of 1 μV per cm in the case of both copper matrix conductors. A few copper-nickel matrix wires quench at low field and thus a high-current density before a current-sharing voltage appears. At a lower critical current density (higher fields) the copper-nickel matrix wires quench just after the appearance of the current-sharing stage in the voltage but usually below the criterion of 1 μV/cm, see figure 3. This is quite understandable since heat conduction in a copper-nickel matrix is much worse (factor 170) than in the usual copper matrices. As we shall see later the current-sharing stage is only reached provided the test wires are sufficiently fixed. Note that the attainment of the current-sharing stage confirms that the real critical current is measured and not a lower value because of unstable behaviour.

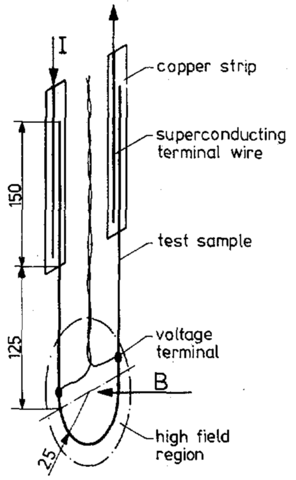

Fig. 2. Arrangement of the superconductor of which the maximum current is measured.

Results obtained for direct currents

The results of the d.c. maximum current measurements are shown in figure 4. Some conclusions can now be drawn from the values found:

- The difference between the largest and the smallest maximum current density is about a factor 2 in the field range considered.
- The current densities in multifilament conductors with copper-nickel matrices made by various manufacturers show large systematic differences.
- The current density in copper-nickel matrix wires at fields between 1 and 3 tesla can be a factor 1.5

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Table 1. Data of twelve NbTi sc. wires. Number of filaments N_{fil}, wire diameter D_{wire}, filament diameter d_{fil}, matrix to sc. ratio λ and sc. to composite ratio η, measured maximum current I_m, current densities in the superconductor J_{sc}, the average current density $\bar{J}$.

wire code	manufacturer	matrix	N_{fil}	D_{wire} [µm]	d_{fil} [µm]	λ	η	I_m(3T) [A]	I_m(5T) [A]	J_{sc}(3T) [kA/mm^2]	$\bar{J}$ (3T) [kA/mm^2]	J_{sc}(5T) [kA/mm^2]	$\bar{J}$ (5T) [kA/mm^2]
W1	MCA	Cu30Ni	1	110	87	0.60	0.625	11.5	7.0	1.94	1.21	1.18	0.74
W2	MCA	Cu30Ni	114	127	7.8	1.35	0.426	19.2	12.0	3.56	1.52	2.22	0.95
W3	MCA	Cu30Ni	114	203	12.4	1.35	0.426	46.0	27.2	3.34	1.42	1.97	0.84
W4	MCA	Cu30Ni	574	200	5.8	1.10	0.476	50.5	32.5	3.38	1.61	2.17	1.03
W5	MCA	Cu30Ni	574	220	6,3	1.10	0.476	63.0	41.5	3.48	1.66	2.29	1.09
W6	MCA	Cu30Ni	574	295	8.5	1,10	0.476	111	68.5	3.41	1.62	2.10	1.00
W7	IMI	Cu25Ni	61	50	4.2	1.35	0.426	1.5	1.0	1.79	0.76	1.30	0.55
W8	IMI	Cu25Ni	61	250	20.9	1.35	0.426	51.5	33.4	2.46	1.05	1.60	0.68
W9	IMI	Cu25Ni	402	250	9.2	0.48	0.676	62.0	32.5	1.87	1.26	0.98	0.66
W10	SUPERCON	Cu30Ni	354	210	7.4	1.30	0.435	39.0	23.3	2.59	1.13	1.55	0.67
W11	MCA	Cu	367	203	7.1	1.25	0.444	39.5	28.7	2.74	1.22	1.99	0.89
W12	MCA	Cu	367	279	9.7	1.25	0.444	68.0	49.6	2.50	1.11	1.82	0.81

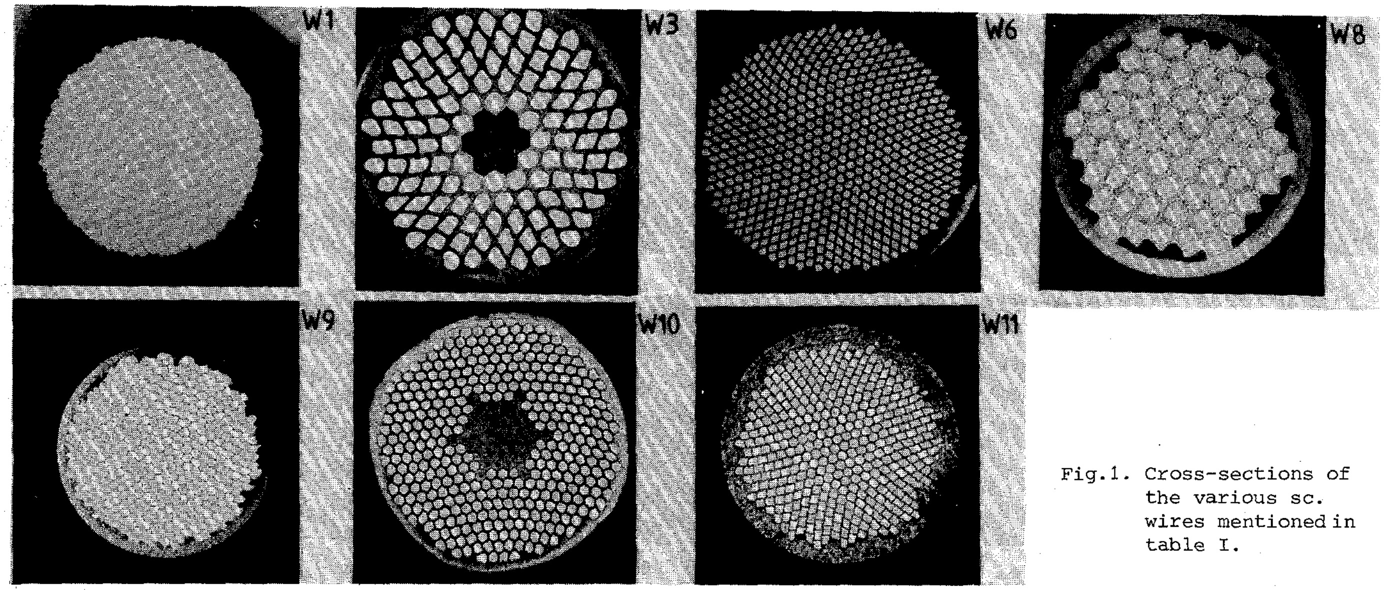

Fig.1. Cross-sections of the various sc. wires mentioned in table I.

higher than the current density in copper matrix wires although both types were made by the same manufacturer. The effect disappears at 6T and may even be reversed above 6 T.

In the region below 1 T, the maximum current density is lowered by the insufficient thermal electromagnetical stability of the copper-nickel matrix wires.

Critical current and stability

There are a number of stability theories which attempt to describe the observed current degradation at high current densities. In the case of NbTi/CuNi wires the sc. filament alone can absorb a certain amount of energy without heat exchange with the matrix. This situation leads to the well-known adiabatic stability criterion which prescribes a maximum diameter of a filament:
$d_{fil} < 0.5\,\pi\, J_c^{-1}\,[C_{sc}(T_c - 4.2)/\mu_0]^{\frac{1}{2}}$, where C_{sc} is the specific heat of the superconductor (2.8 kJ/m^3). It follows from this criterion that at $J_c = 10 * 10^9$ (0 T), $7.5 * 10^9$ (1 T) and $5 * 10^9$ (2 T) A/m^2 the maximum filament diameters are respectively 16, 21 and 30 µm. All the multifilamentary conductors mentioned in table I have sufficiently thin filaments. However, it is surprising to perceive that the monofilament conductor W1 with a core of 87 µm shows a stable performance down to zero field and a current density of 10 kA/mm^2. This behaviour, which is in conflict with the mentioned criterion, has also been previously observed[3].

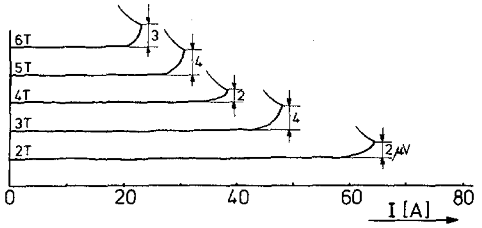

Fig. 3. Voltage across 8 cm superconductor versus current at 2 to 6 T, wire W4.

A second adiabatic criterion called the self-field stability criterion, prescribes the maximum diameter of a multifilamentary wire in stead off the diameter of a single filament:
$D_{wire} < \eta^{-1}\, J_c^{-1}\,[32C(T - 4.2)/\mu_0]^{\frac{1}{2}}\, f(i)$ where $f(i) = [-i^2 - 2i - 2\ln(1 - i)]^{-\frac{1}{2}}$, $i = I/I_c$ and C the specific heat of the multifilamentary composite. The reader can find a discussion about the background of both criteria in reference[4]. Using the equation for self-field stability it is possible to calculate the maximum stable current in a certain wire with diameter D provided J_c is known. The $J_c(B)$ relation at low fields can be found by plotting J_c^{-1} versus the total magnetic field in the wire which is the sum of the applied field and the self-field. Figure 5 shows that the critical current of conductor W6 is well-described by the KIM relation
$J_c(B) = 1.43 * 10^{10}\,[1 + |B|]^{-1}$, $(0 < |B| < 3.5\ \mathrm{T})$.
The calculated maximum stable current in accordance with the mentioned self-field criterion is shown

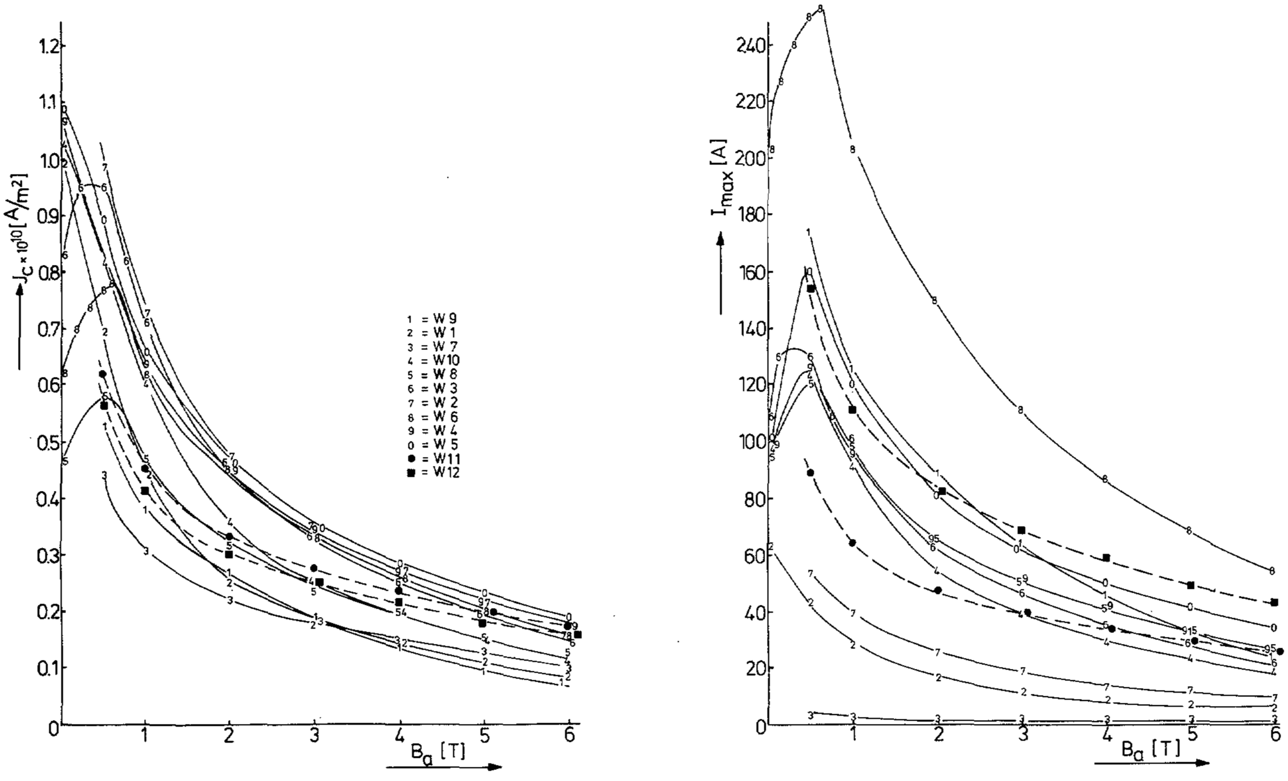

Fig. 4. The measured maximum currents and related current densities in the superconductor.

in figure 6. Moreover the maximum currents for wire W6 measured under three different conditions of the joints between the wire and the current terminals are indicated in this figure.

The effect of the joints

We experimentally determined the effect of two joint locations, two joint geometries and various joint lengths on the maximum current measurements of wire W6. The first measuring condition was: a joint length of 15 cm, joints located outside the high field (fig. 2) and made between the test sample and a superconducting current terminal. This condition gave reproducable maximum currents which equal the critical current for fields above 0.8 T, see figure 6. If the sample is connected to normal conducting terminals (copper strip) lower maximum currents are found below 3 T. If the entire sample including the joints is located in the applied field (type III) the maximum currents are lowered further although they are still larger than those predicted by the self-field stability criterion.

The effect of a reduced joint length than 15 cm is illustrated in figure 7. Without discussing here a physical model of the current transfer from the terminal to the test wire with CuNi matrix we can conclude from the above mentioned results that the measurement of critical currents in a NbTi/CuNi wire at low magnetic fields is very sensitive for the current transfer phenomena in the joints. Obviously, the critical spot is located in a joint rather than

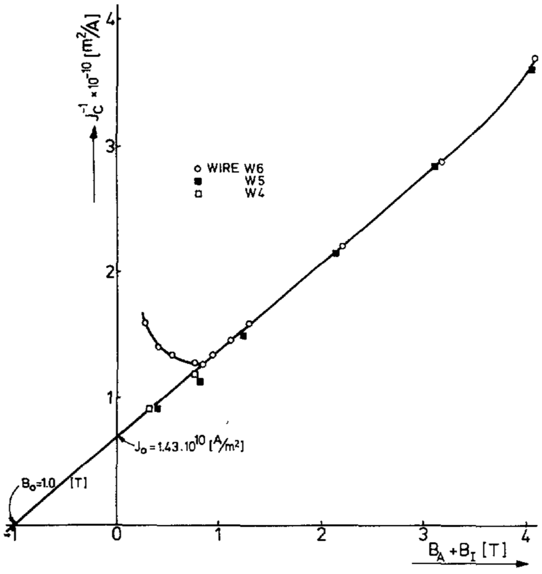

Fig.5. Plot of J_c^{-1} versus total magnetic field, wire W6.

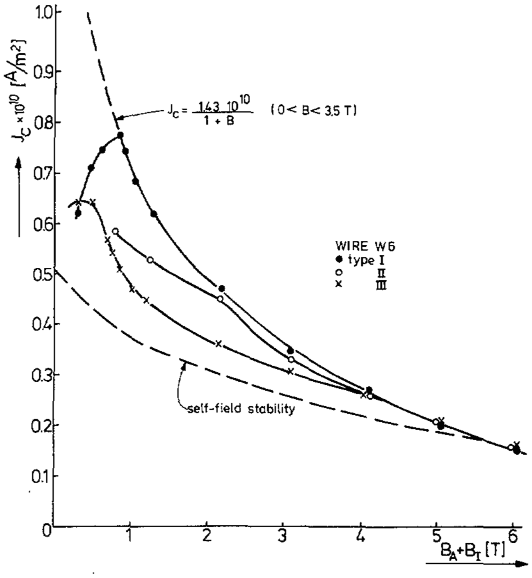

Fig. 6. The effect of the joint on J_c, see text.

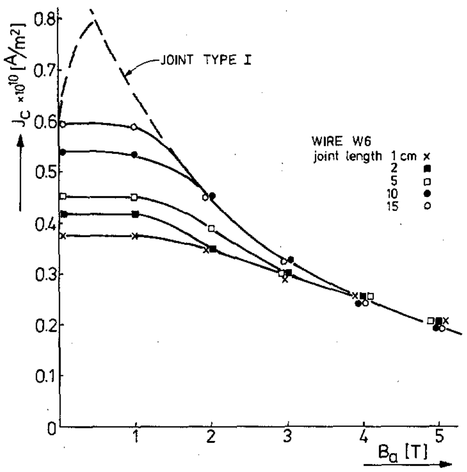

Fig. 7. Shorter lengths of joint type I reduce I_{max}.

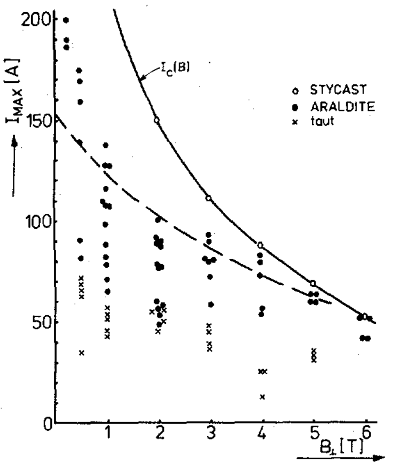

Fig. 8. Three methods of wire fixation give different maximum currents, wire W6.

in the test section if the current transfer is not optimal. Measurements of the quench location confirmed this.

The effect of wire motion

The high resistivity of the copper-nickel matrix has a serious disadvantage in relation to the sensitivity of the wire for energy release due to mechanical disturbances. If, for example, a sc. wire carries a current of 50 A in a magnetic field of 2T, a displacement of 1 μm over a length of 10 mm corresponds to a work of 1 μJ. A small fraction of this work is nonelastic and can be sufficient to initiate a quench. Energy release in the surrounding material of a sc. wire, caused for example by cracking in the impregnant of the coils and cables, can be a source outside the wire.

The minimum length ℓ at which a normal spot in a sc. wire propagates is, assuming adiabaticity, is approximately given by $\ell = 2\lambda(T_c - 4.2)/\rho\ J^2$ where λ is the thermal conductivity in the wire and ρ its resistivity. In the case of a copper-nickel matrix wire we obtain a minimum propagation zone of 3.10^{-11} m if $J = 10^9$ A/m^2 , $\lambda = 1.5$ W/mK and $\rho = 4.10^{-7}$ Ωm. A local heat release of 7.10^{-14} J in a wire with a diameter of 0.3 mm is sufficient to create an overcritical normal spot. This in contrast to a copper matrix superconductor which yields 5.10^{-5} J.

The extreme sensitivity of copper-nickel matrix superconductors to mechanical disturbances was experimentally investigated by repeating the maximum current measurements with two alternative methods of fixing the wires on the sample holder. The previously presented results (fig. 4) were obtained by fixing the conductor with an Al_2O_3 filled epoxy (STYCAST 2850 FT). The results are now discussed about the use of an unfilled epoxy (ARALDITE) for fixing the wire or pulling it into a slit and gluing it at intervals. Figure 8 shows a comparison of maximum current measurements obtained from the three different methods of wire fixation for wire W6. The other wires having a copper-nickel matrix show a comparable behaviour.

We can now conclude that the spread of the results decreases with increasing wire fixation and that fixing the conductors with an unfilled epoxy is insufficient to obtain reliable operation and to measure the critical current. Obviously the difference in thermal contraction of unfilled epoxies and the wire, even if the layer is thin, causes minute cracks in the bulk of the epoxy and at the metal epoxy interface. The energy release in these cracks or the resulting wire motion is sufficient to lower the maximum current and cause unreliable operation since total transitions to the normal state at very low currents also appear. A correct method to determine whether or not the wire fixation is optimal is to check the presence of the current-sharing voltage just before the critical current is reached. This is not observed in the case of degraded performance. In addition to this it should be mentioned that both the copper matrix wires tested showed no trace of these effects and performed a fully stable and reproducible critical current.

Conclusion

The current-carrying capacity of several sc. wires and made by various manufacturers were investigated. It appeared that there are considerable differences in performance of these wires.

Correct measurements of critical currents in copper-nickel matrix wires are difficult to perform because the current transfer to the sample wire and the fixation of the sample are much more critical than in the case of copper matrix wires.

Superconductors having a copper-nickel matrix proved to be very sensitive to mechanical disturbances. Wire motion on a very small scale can easily limit the maximum current by a factor two and is therefore an important consideration in the design and production of sc. devices using this type of wires.

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