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Critical current in NbTi wires irradiated by neutrons at 20 K

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Abstract

In the present paper the results of experimental investigations of NbTi superconducting wires are given with two different treatments: cold-deformed (CD), intermediate thermal treatment (ITT) and also NbTi multiwire of factory treatment. The influence of neutron irradiation on the critical current I_c dependence on magnetic field was studied in the cryochannel of nuclear reactor. Integral neutron fluence of 3×10^{18} cm^{-2} in one core wires increases I_c for CD samples, but doesn't change for ITT samples. Integral neutron fluence of 1.6×10^{18} cm^{-2} leads to substantial I_c-degradation for multiwire, its value undergoes twofold reduction, that is due to the decrease of the working cross-section of the optimized superconducting buses at the expense of its presurface layer 'spoiling' as a result of enrichment by foreign atoms from the matrix of stabilizer.

1. Introduction

NbTi alloy as the possible basic material for superconducting magnetic system (SMS) used in thermonuclear installations and accelerator technique is of great interest. The technology of preparing the multiwires on the base of NbTi alloy achieved the high level and enables to product the current carier elements (multiwires and buses) for powerful SMS. The articles made of NbTi alloy possess high superconducting characteristics: the temperature of superconducting transition $T_c = 8-10$ K, critical current density $J_c = (0.2 - 2) \times 10^4$ A/cm^2 at 4.2 K in magnetic field 5 T, upper critical magnetic field $B_{c2} = 9-13$ T at 4.2 K [1]. This alloy is especially interesting as proper thermomechanic treatment leads to extraction of α-Ti (hcp-structure) in it with critical temperature of superconducting transition $T_c < 2$ K. And extraction of the normal phase of α-Ti particles (superconductors operate mainly at $T > 2$ K) creates good conditions for pinning centres formation, that increases critical current I_c of alloy, if such particles have proper size and distribution. From the phase diagram of NbTi alloy it is known [2], that above 885°C there is the region of β-phase solid solution (bcc-structure) for a whole concentration range of Nb-Ti system. On quenching the high-temperature β-phase the metastable phases α′, α″ and ω are formed. The α′-phase (hcp-structure) undergoes the martensit transformation and converts into orthorhombic α″-phase. The relaxation of NbTi-alloy at temperatures 300–500°C, in which after quenching β-phase was remained, leads ω-phase creation, but this time by means of diffusion as this increases Nb-concentration in existing β-phase [3]. β-phase fixing at room temperature occurs NbTi alloying with elements stabilizers (Cu, Pb, Bi). The transformation takes place according the scheme [4]

$$\beta \rightarrow (\omega + \beta_r) \rightarrow (\beta_e + \alpha), \qquad (1)$$

where β is the initial phase, β_r the phase enriched by stabilizing element, β_e an equilibrium phase. Since the size of magnetic fluxoids in NbTi achieves ≈10 nm, the variation of α-phase size and its distribution allows to achieve high values of T_c in this alloy.

The aim of the present work is to investigate the influence of the field dependence of I_c for a samples of NbTi with different initial microstructure.

2. Experimental

Investigated samples were the wires obtained by the drawing of NbTi alloy in the copper shield up to the diameter of 50 μm. The first group of the samples was obtained by the deformation at room temperature

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(CD-samples). The second group of the samples was obtained by the drawing with intermediate thermal treatment at 370°C (ITT-samples). The third group was the industrial 37-core superconducting wire of 0.7 nm in diameter.

Electron microscopy and X-ray analysis show that wires had subgrains of cross-section 25–50 nm stretched along the drawing direction. Inside the subgrains there where the dislocations. In ITT-samples the reflexes of α-phase extractions were observed along with reflexes of β-phase. There were no discovered α-phase extractions in CD-samples.

The irradiation of the samples was carried out in the cryochannel of the nuclear reactor IRT at 20 K [5]. The fluence of fast neutrons (E > 0.5 Mev) for CD and ITT wires was 3×10^{18} cm^{-2} and for industrial multiwire was 8.6×10^{17} cm^{-2} and 1.6×10^{18} cm^{-2}.

The field dependence of I_c (at 7 K) was determined by contactless method [6] both before irradiation and after attaining the definite neutron fluence.

It should be noted that at transferring the samples from irradiation zone to the testing zone (inside the channel) its temperature decreased from 20 K to 7 K and therefore the radiation defects generated at 20 K were frozen (except those defects which were annealed during the irradiation).

3. Results and discussion

The results of investigations of the low-temperature neutron irradiation influence on the field dependences of critical current for CD and ITT superconducting wires are given in Fig. 1. It is seen that for CD-samles I_c increases after irradiation by neutron fluence of 3×10^{18} cm^{-2}. For example, in the field $B = 5$ T critical current increases by 0.07 A, that makes ~20% of the initial value. At the same time I_c practically doesn't change for ITT-samples irradiated under the same conditions.

More strongly the neutron irradiation influences on the critical current of the industrial multilayer. From the results of Fig. 2 it can be seen that at the reactor irradiation I_c decreases considerable for such wire. In that case the degradation of I_c is not the linear function of the neutron fluence. Indeed, if the irradiation by neutron fluence 8.6×10^{17} cm^{-2} decreases I_c from its value of 300 A in magnetic field $B = 3.5$ T at 7 K down to 160 A, then twofold increase of neutron fluence (up to the 1.6×10^{18} cm^{-2}) leads to its subsequent reduction only to the value of 150 A.

The effect of significant I_c decrease in multiwires was also observed by other investigators [7,8]. It should be noted that such effect was discovered in samples with developed cell-structure, in which I_c was sufficiently high before irradiation. It was shown that high values of I_c in this samples were mainly due to the combination of high density of dislocations in the cell walls with α-Ti extractions, which were highly effective pining-centres of

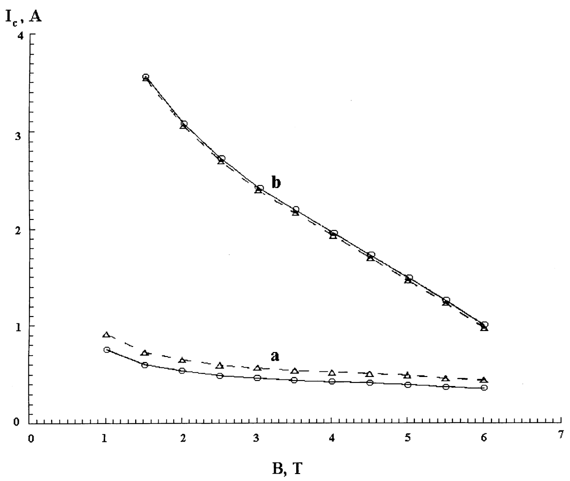

Fig. 1. Dependence of critical current vs magnetic field at 7 K for superconducting wires CD (a) and ITT (b): (○) before and (△) after irradiation by the fast neutron fluence of 3×10^{18} cm^{-2} at 20 K.

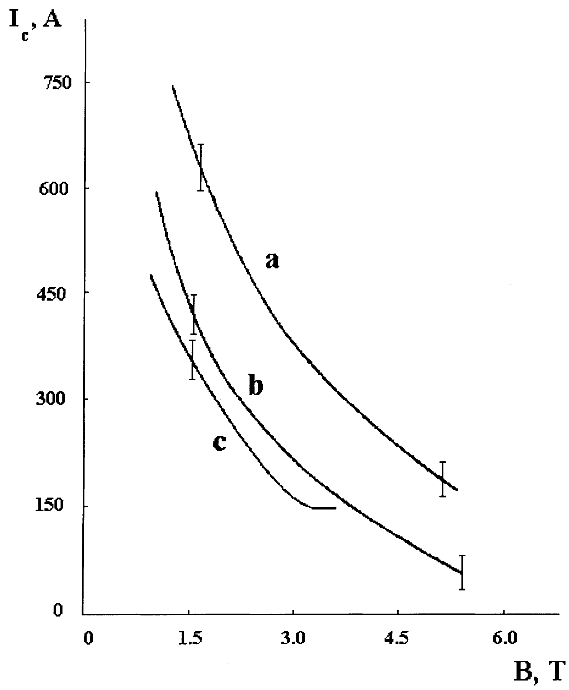

Fig. 2. Dependence of critical current vs magnetic field for 37-core industrial superconducting NbTi wire: (a) before irradiation; (b) after irradiation by the neutron fluence of 8.6×10^{17} cm^{-2}; (c) after irradiation by the neutron fluence of 1.6×10^{18} cm^{-2}.

magnetic fluxoids. It was also shown that with decrease of all sizes the volumes of which are practically free of dislocations, I_c increases according the law

$$I_c \sim 1/d, \tag{2}$$

where d is the size of the cell.

In the samples investigated by us the size of the mentioned subgrain cells were 25–50 nm and therefore it's reasonable to state, that high values of I_c are connected with fluxoids attachment to the walls of these cells and also to extractions of α-Ti.

At irradiation of NbTi superconducting alloy with developed cell-structure and with extractions of α-Ti the radiation damages arise in the cells volume, capable to cause the pinning of fluxoids. This is evident also from the continuous linear increase of resistivity increment for NbTi alloy irradiated under the same conditions [9]. However, the increase of the defects density in the cell volume reduces the partial contribution to the pining force from each wall defect structures, α-Ti extractions and cell volume, resulting in fluxoids effective pinning decreases. Such explanation of I_c radiation degradation suggested in [8,10] taking into account the possibility of radiation destruction of the low dispersional extractions of α-Ti is apparently the more acceptable nowadays.

It is worth to mention that at irradiation of superconducting wires the additional factors appear, which may influence on the radiation degradation of the current carrier ability. Superconducting cores in the matrix stabilizer (mainly an alloy on the base of Al and Cu) would be irradiated by nuclear particles under such conditions when they experience the influence of compressive stresses as a result of its cooling down to the helium temperatures. The radiation damages arising under the compressive stresses at cryogenic temperatures may involve the considerable regions formed by penetration of focusing and channeling particles at more large distances. We think that at wire irradiation (composition in fact) the 'decoration' of the core surface layer by foreign matrix atoms should also take place which in its turn leads to decrease of its working cross-section.

4. Conclusions

It is established experimentally that (1) the irradiation of superconducting NbTi wire by neutron fluence of $3{\cdot}10^{18}$ cm^{-2} at 20 K leads to: (a) I_c increases in CD-samples by $\approx$20%; (b) I_c practically does not change in ITT samples; (2) the irradiation of an industrial multicore wire of NbTi by neutron fluence of 1.6×10^{18} cm^{-2} at 20 K results in I_c substantial degradation – namely twofold reduction of its value.

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