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Influence of Radiation Induced Nano-defects on Critical Current of HTc Superconductors

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Superconductors, including HTc materials are more and more frequently used in modern nuclear physics devices. During the work of nuclear accelerators arises however the radiation of heavy ions or fast neutrons, which can reach the superconducting windings, creating nano-sized defects. It influences properties of superconductors. In the paper is given theoretical analysis of the influence of nano-defects on the critical current of HTc superconductors. New theoretical model of the critical current is proposed based on an analysis of the interaction of nano-defects acting as pinning centers with pancake vortices appearing in HTc superconductors. Nano-defects from one side destroy the structure of superconducting materials, which effect has negative meaning, while from other side anchorage of individual vortices or vortex lattice on defects will improve critical current. These both opposite phenomena are considered for HTc materials and also for A15 type superconductors, in which superconductivity is strongly related to state of ordering of transition metals as Nb, V in linear chains. The potential barrier against pancake vortices movement has been considered and calculations of an influence of sizes of nano-defects on current-voltage characteristics performed. Expression for an energy barrier allowed also to determine the time stability of the magnetic vortex structure and flowing current, which effect has especial meaning in the superconducting shields.

Keywords: Nano-Sized Defects, Superconductors, Irradiation, Critical Current

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1. INTRODUCTION

High temperature superconductors are more and more widely applied in power engineering, including the case of the accelerators used in the nuclear physics. These materials are however very strongly dependent on the existence in them of the nano-defects, which influence their superconducting properties. Such case has the place just in the nuclear reactors, in which superconducting materials are used as the windings of electromagnets focusing the heavy ions beams. It appears here the neutron irradiation, which creates defects inside the superconductors. These defects influence the critical current as well as other properties of superconductors. To an analysis of appearing there phenomena is devoted present paper.

2. MODEL PRESENTATION

Mathematically, elaborated model is based on an analysis of the change of energy of the system in the case of the appearance of defects in the structure of the superconducting material, interacting with magnetic vortices. Such defects acting as pinning centers, stabilize the magnetic vortices structure and allow therefore for the resistive-less transport current flow. From other side they damage crystallographic structure of superconducting material leading to the destruction of superconductivity. It is well seen in the Fig. 1 showing the crystallographic structure of the superconducting A15 materials, as Nb_3Sn, frequently used in construction of superconducting wires. There are shown here three perpendicular branches of the linear chains of the niobium 3d transition atoms, responsible for superconductivity in these materials. Destruction of the linear chains by neutron irradiation has therefore large meaning for superconducting properties of them.

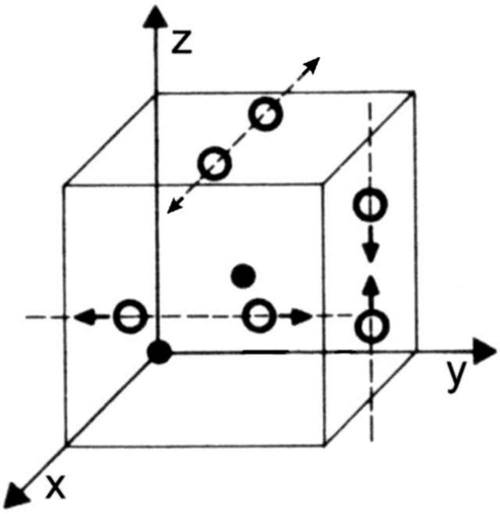

Fig. 1 – Crystal structure of A15 type superconductor, with shown linear chains of transition metals (circles). Dots indicate position of Sn atoms in Nb_3Sn compound

Such degradation effects in A15 type wires are really observed experimentally. It is interesting that although as it follows from Fig. 1 it is rather complicated crystal structure but she is characterized by very high symmetry of the 48 operation, similar to simple cubic lattice. Arrows shown in Fig. 1 indicate the direction of the movement transition metals atoms in cubic A15 type structure during the transition to the tetragonal phase. It appears then the doubling of the lattice constant of atoms in the linear chains, similarly as it has the place in so called Peierls instability – transition between metal and insulator, depending on the magnitude of interaction between individual atoms.

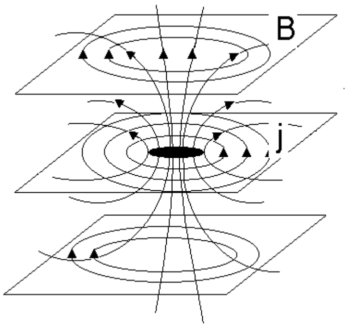

Fig. 2 – The pancake type magnetic vortex in the multilayered structure of the HTc superconductors. B is magnetic induction, while j circular currents density

Interaction of pancake type vortices shown in Fig. 2, appearing in HTc superconductors, with nano-sized defects created by neutron irradiation leads to energy barrier ΔU [1] described by the following relation:

$$\Delta U = \frac{\mu_0 H_c^2}{2} l\xi^2[-\arcsin(\frac{j}{j_c})+\frac{\pi}{2}-\frac{j}{j_c}\sqrt{1-(\frac{j}{j_c})^2}\,] \quad (1)$$

In Eq. 1 H_c denotes thermodynamic critical magnetic field, ι coherence length, which describes the radius of the core of the vortex, while l is thickness of the vortex and μ_0 magnetic permeability. j denotes transport current density, while j_c critical current density. Energy barrier ΔU given by Eq. 1 is composed from pinning potential supplemented by the Lorentz force potential, induced by the interaction of the local current density at vortex and magnetic induction B. Capturing of the vortices decreases the volume of the normal part in superconductors and therefore total energy of system, which results in the potential barrier appearance. Oppositely Lorentz force tears vortex off from an initial equilibrium position, assumed here as vortex captured on the depth of the coherence length ξ inside the pinning centre, reducing thus the potential barrier height with current, as it indicates Eq. 1. Analogous influence has elasticity energy of vortex lattice, caused by deflection of pinned vortex from equilibrium.

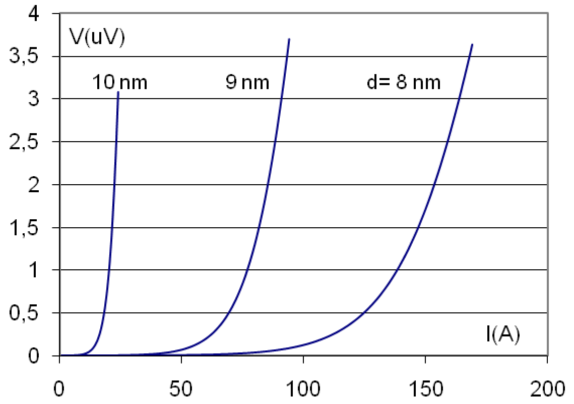

Fig. 3 – The influence of the nano-defect size on the current-voltage characteristic of the HTc superconductor for surface concentration of nano-defects equal to $86 \cdot 10^{10}$ cm^{-2}

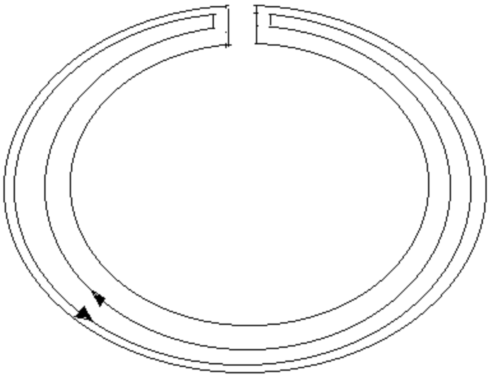

Fig. 4 – Cross-section of the unclosed superconducting shield, with screening currents direction indicated by arrows

Decrease of an energy barrier leads to enhance of a probability of the magnetic vortex movement in the flux creep process, generating thus voltage. Calculated according to presented model current-voltage characteristics for HTc superconducting material, in the function of dimensions of irradiation induced nano-defects are shown in Fig. 3. This figure indicates on important influence of size of nano-defects on critical current. Nano-sized defects, modifying the potential barrier height given by Eq. 1 change too the time stability of the magnetic induction distribution and then critical current of HTc superconductors. This effect is important also for superconducting shields, used for homogenization of magnetic field in superconducting windings. The cross-section of the unclosed superconducting shield is shown in Fig. 4, while distribution of surface currents in upper (Fig. 5a) and bottom (Fig. 5b) cover of such shield presents schematically Fig. 5.

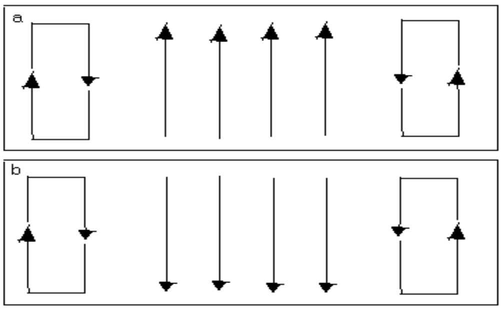

Fig. 5 – Shielding currents distribution in the upper (a) and bottom (b) cover of the superconducting unclosed shield

Basing on Eq. 1 has been received approximated Eq. 2, predicting time relaxation of current flow in creep process, in function of material parameters t_1 and β:

$$\frac{j(t)}{j_c} = const - \beta \ln(1+\frac{t}{t_1}) \quad (2)$$

Such dependence is really observed experimentally.

REFERENCES

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