Inhomogeneity and irreversibility field of superconducting Nb-Ti tapes

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Abstract. Magnetizations and current-voltage characteristics of superconducting tapes from Nb-50% wt.Ti alloy are studied. In the region of external magnetic fields close to the upper critical field, there is a so called irreversibility field, which is often associated with the phase transition of vortex matter. However, in this study it is shown that the whole volume of experimental data can be described if we abandon the hypothesis of a phase transition and go over to the hypothesis of macroscopic inhomogeneity. This hypothesis implies the existence of two superconducting components with different upper critical fields, which naturally arise as a result of the production process.

1 Introduction

One of the most puzzling questions in the modern thermodynamics of vortex matter in type-II superconductors is the nature of the so-called irreversibility line in the field-temperature (H-T) phase diagram. At a fixed temperature, the irreversibility field $H^*(T)$ can be defined as the field above which there is no hysteresis (irreversibility) of the magnetization loop $M(H)$, but nevertheless the superconducting state is conserved. Usually, in high-T_c oxide superconductors, simultaneously with the appearance of reversibility, the critical current density reduces to zero, so $H^*(T)$ is also an important parameter for applications [1].

A number of models have been proposed to explain the existence of the irreversibility line in high-T_c oxide superconductors [2]. Regardless of the mechanisms, it seemed that consensus was reached on what is the main cause of this phenomenon: a large anisotropy in electronic properties (layered structure) and a high impact of thermal fluctuations. However it was later discovered that the irreversibility field is not unique to high-T_c oxides, but also exists in conventional superconductors such as Nb [3], Nb_3Sn [4], Nb-Ta [5] and Nb-Ti [4-6], which are supposed to be isotropic and weakly subject to thermal fluctuations due to low operating temperatures. Attempts to apply existing models of the irreversibility field to low-T_c superconductors have led to the fact that the most adequate phenomenological description is given by the model of the flux lattice melting [3, 4], although the validity of this model gives rise to doubt, as due to high pinning in commercial superconductors, the vortex matter should be in a glass state below $H^*(T)$ [7].

In this study it is shown that in the Nb-Ti tape the hypothesis of a phase transition of a vortex matter to a liquid state is not consistent. Moreover, in order to describe the phenomenon of the irreversibility field, it is not necessary to resort this hypotheses, it is sufficient to take into account the inhomogeneity that naturally arises in the fabrication process. Such a model of the irreversibility field fits concordantly into modern concepts of pinning mechanisms in conventional cold-worked (rolled or drawn) superconducting alloys.

1.1 Flux pinning mechanism and electrodynamics in high magnetic fields of cold-rolled Nb-Ti tape

It is well known that in single-phase cold-rolled superconducting alloys at high degree of deformation, the main mechanism of the pinning is a pinning at the grain boundaries [1]. At the microscopic level, the main reason for pinning is the decrease in the mean free path of conduction electrons near the grain boundary, which leads to a local decrease in the coherence length. Thus, the size of vortex core is effectively reduced, self-energy of the vortex is decreased and it is energetically favorable for vortex to remain near the grain boundary. This model allows one to unequivocally describe the main experimental facts in a wide range of magnetic fields, namely, the anisotropy of the pinning force in cold-rolled tapes, the guided motion of the vortexes, the growth of the critical current with increasing field in small magnetic fields and etc. [8]. Such a local decrease in the coherence length leads to the fact that the upper critical field is locally increased there, as the relation between these quantities is [1]:

$$\mu_0 H_{c2}(T) = \Phi_0 / 2\pi\xi(T)^2 \qquad (1)$$

where Φ_0 - flux quantum, ξ - coherence length, H_{c2} - upper critical field. Thus, in a range of sufficiently high

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magnetic fields, it is to be expected that the grain bodies will transform into a normal state, while the grain boundary will still be superconducting. Indeed, this division into two superconducting components with different H_{c2} has been observed experimentally earlier: through the features of the appearance of the satellite electric field [9], and through the apparent anisotropy of the upper critical field [10].

2 Methods and samples

The irreversibility field has been investigated on a cold-rolled Nb-Ti tape. Electrodynamics and the structure of this tape have been studied in details by our group earlier [8-10]. This is a single-phase tape of the Nb-50%wtTi alloy, with the pinning due to the reduction of the mean free path of the electron at the grain boundaries. Besides, the tape has been investigated after additional heat treatment in high vacuum at 385 ˚C during 25 hours. As a result, 6% by volume of α-Ti have been precipitated. This has changed the pinning mechanism sensibly, bringing it closer to the mechanism which is implemented in commercial NbTi wires.

The magnetization loops were measured in a shunted superconducting magnet up to 13 T in liquid helium, by a couple of Hall sensors, under one of which a sample was placed. Thus, the magnetization was determined from the difference of the signals. The magnetic field was oriented orthogonal to the plane of the Nb-Ti tape. For the purpose of amplification the wanted signal, the tested samples were stacks of 10 tapes cut in the form of a square 6 mm x 6 mm. The field sweep rate was controlled by the sweep rate of solenoid current and was approximately 0,008 T/s.

Transport measurements were carried out in the same superconducting solenoid. Flat samples, adhered to dielectric corundum substrate, with bridge geometry along the rolling direction were made by laser cutting (the bridge was 1.0 mm in width and 6.7 mm in length) by analogy with [10]. In all experiments, the field was perpendicular to the plane of the tapes, so the pinning force was determined as a simple product of the field and the critical current density, determined by the criterion 1 μV/cm.

3 Results

Figure 1 shows experimental data from the magnetization, the pinning force density and resistivity as a function of applied field for the cold-rolled NbTi tape. A linear background signal, which is present above H_{c2}, has been subtracted from the magnetization data (fig. 1a), and hence the curve becomes flat at fields beyond H_{c2}. After the collapse of the $M(H)$ loop at the field H^{*}~10.6, one can see a weak but reproducible inverse (ferromagnetic) hysteresis whose nature is difficult to explain. The hysteresis completely disappears in fields above ~11.3 T. Since the value of this hysteresis is only about 2 times greater than the noise, the

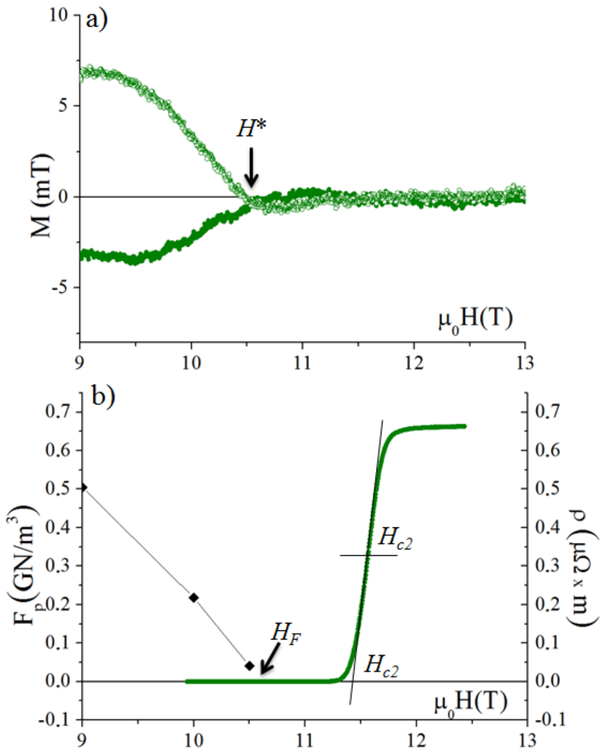

Fig. 1. Experimental magnetization, pinning force, and resistivity data for cold-rolled NbTi tape as a function of applied field. An extricating current of 5 mA was used for resistivity measurements

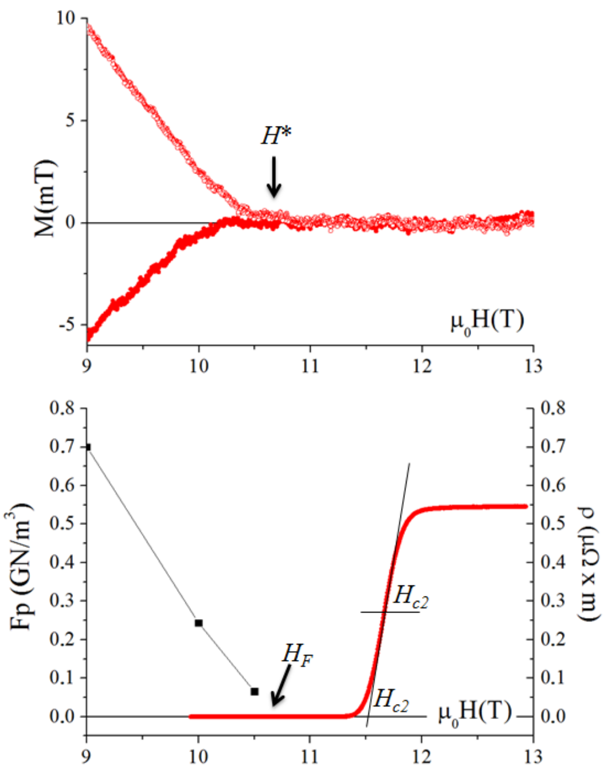

Fig. 2. Experimental magnetization, pinning force, and resistivity data for heat-treated NbTi tape as a function of applied field. An extricating current of 5 mA was used for resistivity measurements.

magnetization can be regarded as reversible. No pronounce changes in the slope of reversible magnetization around H_{c2} have been observed. This is possibly related to roughness of used method.

The irreversibility field has a clear correlation with the extrapolation of the pinning force to zero ($H_F \sim$ 10.6T) (fig. 1b). The upper critical field (H_{c2} = 11.6T) has been determined from measurements of the resistivity with an exciting current of 5 mA. It was shown in [10] that a decrease in the current below does not lead to a significant shift in H_{c2} determined in the middle of the transition. An alternative way to determine upper critical field [6] by the intersection of the linear extrapolation of the resistive transition through the baseline voltage gives value H_{c2}=11.4 T. Thus, the difference between H^* and H_{c2} is about 0.9 T.

Experimental data for heat-treated sample are shown on figure 2. After heat treatment, the normal resistance has decreased by 20% and pinning in the 9 T field has increased by 40%. As in the case of cold-rolled, no changes in the magnetization slope near H_{c2} (11.5T or 11.7T, depending on the criteria) are observed, there is a clear correlation between H_F (10.6T) and H^* (10.6T) and the difference between H^* and H_{c2} is about 1T.

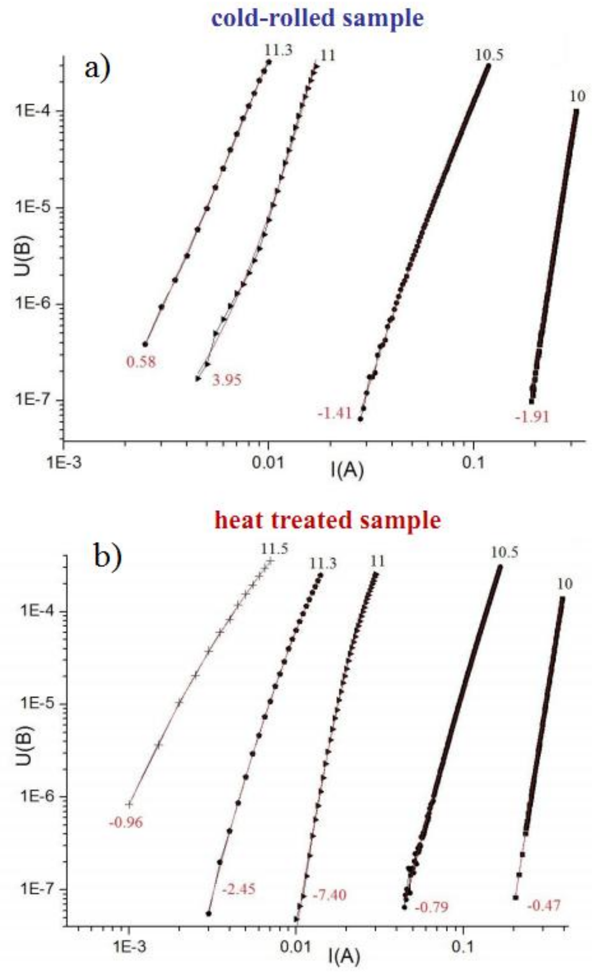

Fig. 3. Current – voltage characteristics in log-log scale for cold-rolled (a) and heat-treated (b) tapes. The value of magnetic field is signed from above of each CVC; the value of the coefficient in front of the quadratic term of approximation is signed from below each CVC.

The irreversibility field is often associated with a vortex matter phase transition. A common practice of the identification such a transition is to analyze the current – voltage characteristics (CVCs) plotted in log-log space. The transition identified as the field at which the CVC curvature changes sign. Figure 3 shows the CVCs in double logarithmic scales for different values of an external magnetic field (signed from above in Tesla), and also approximations (thin red lines) by quadratic fit. The values of the coefficient of the second order of this approximation are signed below each CVC.

4 Discussions

The obtained data validate the existence of the irreversibility field both in cold-rolled and heat-treated Nb-Ti tapes. The hypothesis of the phase transition of vortex matter from glass state to liquid state, as the cause of the irreversibility field, clearly fails, as can be seen from Fig. 3. Indeed, in accordance with modern concepts, one of the necessary conditions for the phase transition of the vortex matter is the change in the curvature of CVCs at the irreversibility field [11]. At that, in the fields below the irreversibility field, all CVCs have a negative curvature; in fields above the irreversibility field they have a positive curvature. For the cold-rolled tape, some experimental CVCs change the curvature several times, which contradicts the model of the vortex matter phase transition, in which the curvature should be either positive or negative. For the heat-treated tape, all the CVCs have a negative curvature up to the upper critical field.

On the other hand, in the statistical inhomogeneity model, the changes in the sign of the CVC curvature do not have a deep physical meaning, but are determined by the specific character of the inhomogeneity of the sample [12].

The fact that the irreversibility field has a clear correlation with the extrapolation of the volume pinning force, what was also observed in [6], hints at the fact that both characteristic fields are a manifestation of a single physical phenomenon. It was shown in [9, 10] that in the fields above H_F only the grain boundaries remain in superconducting state, while the grain bodies become normal. This mechanism gives a qualitative explanation for such dramatic decrease in the critical current and the appearance of reversible magnetization, since superconducting currents are mainly caused not by pinning, but by reversible surface currents.

As a result of the rolling, the grains of NbTi are flattened; therefore in fields above H^* the cold-rolled NbTi tape becomes a strongly anisotropic superconductor, which can be roughly represented as a stack of superconducting films (grain boundaries) [10]. This fact makes it possible to draw a formal analogy with high-T_c layered superconductors with a large parameter of anisotropy. As a result of heat treatment, α-Ti particles are precipitated at the grain boundaries, disrupting their flatness and decreasing the anisotropy [10], the pinning force is enhanced substantially, but the irreversibility field remains unchanged. Thus, the irreversibility field is not directly related to the pinning force in low-T_c superconductors, as it is usually assumed in models which attach to thermal fluctuations a decisive role in the mechanisms of the phenomenon.

5 Conclusion

The field of irreversibility of the cold-rolled and additionally heat-treated NbTi tapes has been investigated. Based on the analysis and generalization of the experimental facts obtained in this work, as well as those obtained earlier in our group, it is concluded that a dramatic decrease in the critical current in fields above the irreversibility field of NbTi tapes is a direct consequence of the inhomogeneity created during production process, in order to achieve high current carrying capacity in lower fields.

References

1. T. Matsushita, *Flux pinning in superconductors* (Springer, 2014)
2. M. Tinkham, IEEE Trans. On Mag. **27** (1991)
3. M. F. Schmidt, N. E. Israeloff, A. M. Goldman Phys. Rev. Lett., **70** (1993)
4. M. Suenaga, A. K. Ghosh, Y. Xu, D. O. Welch, Phys. Rev. Lett., **66** (1991)
5. D. N. Zheng, N. J. C. Ingle, A. M. Cambell, Phys. Rev. B, **61** (2000)
6. M. T. Naus, R. W. Heussner, A. A. Squitieri, D. C. Larbalestier, IEEE Trans. on App. Super. **7** (1997)
7. T. Matsushita, Phys. C **214** (1993)
8. E. Yu. Klimenko, S. V. Shavkin, P. V. Volkov, Zh. Eksp. Teor. Fiz **112** (1997)
9. E. Yu. Klimenko, S. V. Shavkin, P. V. Volkov, Phys. Met. Metallorg. **92** (2001)
10. V. V. Guryev, S. V. Shavkin, V. S. Kruglov, P. V. Volkov, A. L. Vasiliev, A. V. Ovcharov, I. A. Likhachev, E. M. Pashaev, R. D. Svetogorov, Y. V. Zubavichus, J. of Phys.: Conf. Ser. **747** (2016)
11. D.R. Strachan, M.C. Sullivan, P. Fournier, S.P. Pai, T. Venkatesan, C.J. Lobb, Phys. Rev. Lett. **87** (2001)
12. E. Yu. Klimenko, *Superconductivity Theory and Applications* ed. by A. M. Luiz (InTech, 2011)