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Abnormal behaviour of the resistive transition to the normal state in superconducting Nb-Ti tapes just below Hc2

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Abstract. The results of studying the resistive properties of Nb-Ti tapes in high magnetic fields close to the upper critical field (H_{c2}) are reported. The voltage-current curves (VCCs) and resistance-current cures (RCCs) show an "abnormal" hysteresis which is opposite in sign to a common thermal one caused by self-heating. Several features were noted: the existence of threshold current below which VCCs are reversible and the presence of excessive voltage noise in the hysteresis region. Earlier the similar behaviour was observed in granular superconductors. The nature of the "granular" properties of Nb-Ti tapes in high magnetic field and the relation with other observed effects, such as the irreversibility field and the apparent anisotropy of the upper critical field are discussed.

1 Introduction

It is known that due to electron scattering at the grain boundaries in single-phase cold-rolled Nb-Ti tapes the mean electron free path decreases locally. In the superconducting state this leads to a local decrease in the coherence length which makes the grain boundaries as energy-efficient pinning centres [1]. On the other hand, this local decrease of the coherence length near grain boundaries leads to correspondent local increase of the upper critical field (H_{c2}). Thus, there are two kinds of "phases" with different upper critical fields in cold-rolled Nb-Ti tape: grain boundaries area (GB) and internal volume of grains (bulk). In magnetic field near upper critical value, this combination of two components results in the peculiarities of the accompanying electric field appearance [2], and in the apparent anisotropy phenomenon of the upper critical field [3]. Moreover, within this model a quite puzzling irreversibility field (H^*) phenomena can be explained [4, 5]. In fact, the irreversibility field point is the field value at which the bulk of grains drops from superconducting into normal state and the grain boundaries net remain as the only superconducting component. Macroscopically this shows itself as the transition from irreversible to reversible behavior of the magnetization versus magnetic field. As the result, in the range of field between H^* and H_{c2} the Nb-Ti tape is in a quite rare electromagnetic state in which it can transfer finite superconducting current, but the magnetization behavior is reversible.

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In this paper we present the results of a further study of this unique state in Nb-Ti tapes in the range of magnetic fields above H^* by means of a detailed analysis of the voltage-current curves (VCC). As the critical current above the irreversibility field are substantially reduced, this makes it possible to investigate the CVC over a wide range of voltages up to the transition into normal state without significant self-heating.

2 Samples and methods

We used thin cold-rolled Nb-Ti tape (thickness 10 μm) which structure was studied earlier [6,7]. Nb-Ti grains are elongated in the rolling direction and flattened in the normal to tape direction. The average grain sizes in the normal direction is 65 nm, in the direction perpendicular to the rolling (in the plane of the tape) ~ 0.3 μm and in the rolling direction – more than 1 μm [3, 6].

For comparison we also investigated this Nb-Ti tape after heat treatment. The heat treatment was carried out at a residual pressure of 10^{-2} Pa at 385 °C for 25 hours. After heat treatment about 6 vol.% of non-superconducting α-Ti phase was precipitated [7] at the grain boundaries of Nb-Ti in form of small nanoscale particles [6]. The α-Ti particles led to a significant change in the grain boundary system, violating their flatness and decreasing the apparent anisotropy effect of the upper critical field [3]. At the same time, the average grain size of Nb-Ti does not change considerably with heat treatment [6].

All samples were prepared from the tape by laser cutting and had a width of 1 mm and the distance of 6.7 mm between potential terminals. Each sample was glued to dielectric corundum substrate, which has a high thermal conductivity at liquid helium temperature and provides additional temperature stabilization.

Measurements of the VCCs were performed by a standard four-terminal method in liquid helium at atmospheric pressure in superconducting solenoid capable of producing the magnetic fields up to 13 T.

3 Experimental results

As a rule, the VCCs were investigated near so-called critical current value. The most common criterion for the critical current is 1 μV/cm. We did not find any irregularities on the VCCs of Nb-Ti tapes in the range of electric fields close critical current criterion.

With increases of the electric field by several orders of magnitude we observed unexpected hysteresis of the VCCs where the return branch of the VCC paths below the forward one. Observed difference of VCCs forms are opposite in sign to possible self-heating hysteresis due to the Joule heat generation. So this is abnormal hysteresis [8]. Figure 1 shows a series of VCCs for a sample of the cold-rolled Nb-Ti tape. The external magnetic field direction was perpendicular to rolling direction and parallel to the tape plane. The upper critical field was 11.9 T for this geometry [3]. As the typical resistance at which the hysteresis observed are close to the resistance of Nb-Ti in the normal state, we replot the VCCs in form of the resistance-current curves (RCCs) (see Fig. 2), as it was proposed in [9].

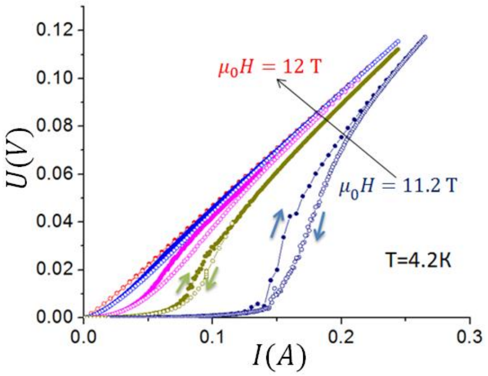

Fig. 1. A series of VCCs for the cold-rolled Nb-Ti tape. The external magnetic field is perpendicular to rolling and lies in the plane of the tape. The value of the magnetic field varies in the range from 11.2 T to 12 T in steps of 0.2 T. Upper critical field for this geometry is $\mu_0 H_{c2}$ = 11.9 T [3].

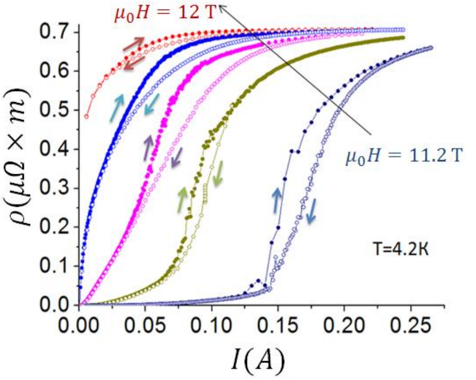

Fig. 2. A series of RCCs for a cold-rolled Nb-Ti tape, replotted from the VCCs (Fig. 1). The value of the magnetic field varies in the range from 11.2 T to 12 T in steps of 0.2 T. For fields of 11.2 T and 11.4 T, it is clearly seen that there is excessive voltage noise in the hysteresis region.

All RCCs demonstrated common features, namely, the presence of excessive voltage noise in the hysteresis region and the existence of a threshold point below which the RCCs are reversible (see Fig. 3). Indeed, if the value of the threshold current (point 1 in Fig. 3) is not exceeded, then the RCCs are completely reversible. If value of the current exceeds the threshold value, the return branch of RCC lies below the forward branch (from point 2 to point 3 in Fig. 3). If we stop at point 3 (before reaching the threshold point) and then increase the current again, a smaller hysteresis is observed (loop 2-3-2). Finally, the maximum hysteresis is observed with increasing current from the threshold value to the appearance of normal resistivity and decreasing the current back to the threshold value (loop 1-4-1).

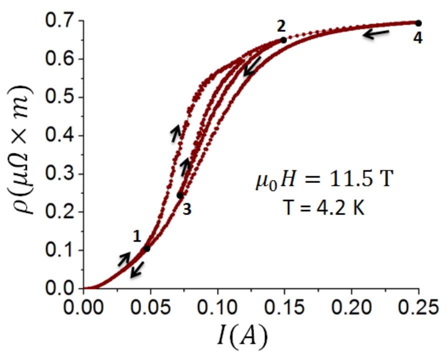

Fig. 3. RCC for the cold-rolled Nb-Ti tape. The field of 11.5 T lies in tape plane. Up to the threshold current value (point 1) the RCC is reversible. If the threshold value is exceeded, an abnormal hysteresis arises, so that the return branch of the characteristic lies below the forward one.

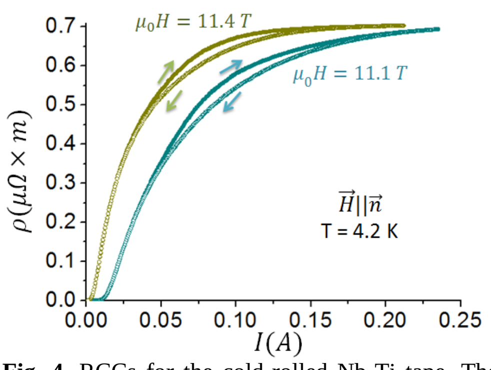

Fig. 4. RCCs for the cold-rolled Nb-Ti tape. The magnetic field (11.1 T and 11.4 T) is normal to the tape. Upper critical field for this geometry is $\mu_0 H_{c2}$ =11.6 T [3].

When the orientation of the external magnetic field is normal to the cold-rolled Nb-Ti tape, these features of the RCCs hysteresis remain qualitatively, but the magnitude of the hysteresis loops significantly decreases. Figure 4 shows the RCCs for a cold-rolled tape for the field normal to the tape.

The magnitude of the abnormal hysteresis in the RCC (as well as the VCC) is significantly reduced after heat treatment of the Nb-Ti tape for the field-in-plane geometry (see Fig. 5). The anisotropy of the hysteresis magnitude with respect to the magnetic field direction almost disappears for the heat-treated Nb-Ti tape (see Fig. 5 and 6)

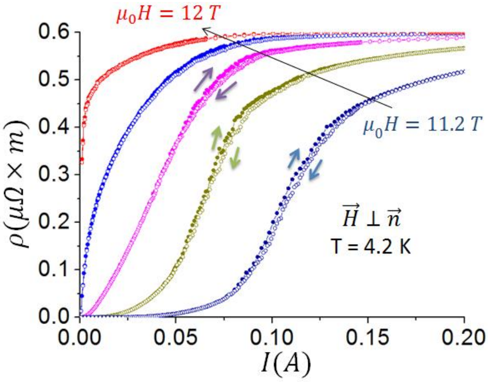

Fig. 5. A series of RCCs for the heat-treated Nb-Ti tape. The external magnetic field is perpendicular to rolling and lies in the plane of the tape. The value of the magnetic field varies in the range from 11.2 T to 12 T in steps of 0.2 T. Upper critical field for this geometry is $\mu_0 H_{c2}$ =11.9 T [3].

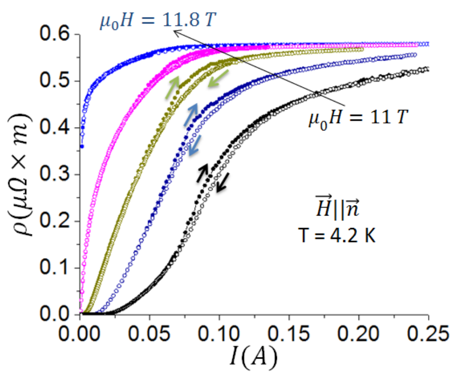

Fig. 6. A series of RCCs for the heat-treated Nb-Ti tape. The external magnetic field is normal to the tape. The value of the magnetic field varies in the range from 11 T to 11.8 T in steps of 0.2 T. The upper critical field for this geometry is $\mu_0 H_{c2}$ =11.7 T [3].

4 Discussion

It was reported earlier that similar abnormal hysteresis of VCCs with abovementioned features was observed on granular superconductors [8, 10, 11]. To explain the nature of this hysteresis two models were proposed: radiation-stimulated superconductivity [10] and a model of granular superconducting glass [8, 11]. In both models, the presence of granular properties (as network of Josephson weak links) is fundamental, which at first sight does not seem applicable to Nb-Ti tapes. However (as described in the introduction) in field higher than irreversibility field (which for Nb-Ti tapes is approximately 10.7 T [4, 5]) only the grain boundaries remain in the superconducting state. The system of grain boundaries for the cold-rolled Nb-Ti tape can be simulated in the form of stacks of superconducting films [3]. In the stacks the films do not have weak links, as the average Nb-Ti grain size in normal direction (~65 nm) is an order of magnitude greater than the coherence length (~ 5 nm). Nevertheless, weak links can arise between the stacks. In this way, granular properties above the irreversibility field can appear in the Nb-Ti tapes.

As the grain boundary system of the cold-rolled tape is highly anisotropic (is a stack of films), then anisotropy of the hysteresis magnitude with respect to direction of magnetic field can be explained naturally. On the other hand, as a result of heat treatment, the grain boundary system becomes more isotropic, losing its flatness. This explains the disappearance of the hysteresis magnitude anisotropy for the heat-treated Nb-Ti tape.

5 Conclusions

In the range of magnetic fields above the field of irreversibility value the abnormal hysteresis of the voltage- current curves was observed for Nb-Ti tapes. This hysteresis is present in the voltage range several orders of magnitude higher than typical superconducting criteria. At such high voltages, the resistance of the material is same order of value with the resistance of the Nb-Ti normal state.

The following features of abnormal hysteresis were noted: (1) the presence of excessive voltage noise in the hysteresis region, (2) the existence of a threshold current below which there is no hysteresis, (3) the presence of anisotropy of the hysteresis magnitude for the cold-rolled tape, and (4) practically no anisotropy in the case of heat-treated tape.

These features can be explained within the framework of the model of the appearance of granular superconductivity. This model agrees with the earlier explanation of the irreversibility field nature for Nb-Ti tape, the apparent anisotropy of the upper critical field of Nb-Ti tape, and the peculiarities of the arising accompanying electrical field.

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