Experimental investigation of the processes of degradation and transition to the normal state in CC-tapes under the action of current pulses

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Abstract. The study of the behaviour of CC tapes under the action of nonstationary current loads was conducted: a transition to the normal state was observed, as well as processes of CC-tape degradation. The obtained data make it possible to solve the problems associated with the creation of high-speed switching devices based on high-temperature superconductors, intended for functioning in superconducting energy storage devices, energy distribution and transmission systems, current limiters, and new types of transport. In addition to superconducting switches, pulsed current loads can occur in the mentioned above systems due to short-circuit conditions or other factors, and can lead to local heating of HTSC, especially if there is an inhomogeneity in the critical current in the CC-tapes. In this work we present the results of a study of non-stationary processes second generation HTS tapes heating under the impulse current loads with amplitudes up to 2.2Ic (77K, self-field). Superconducting tapes with a copper protective layer were used as the samples. The I-V characteristics of the samples were measured under the action of current pulses during cooling in liquid nitrogen. Critical parameters (amplitude, rise time of the transport current) of the current pulses, leading to the degradation of the superconductor were obtained. Local current carrying characteristics of CC-tapes investigated using Hall probe magnetometry.

The features of the influence of local inhomogeneities in the distribution of the critical current of the tapes on the transition of the superconductor to the normal state are revealed.

1. Introduction
An important aspect of the operation of any electrical device is its reliability. For most applications of high temperature superconductors the most unfavorable situation is the moment of transition to the normal state. At the same time, the local heat release is aggravated by the low propagation speed of the hot spot, which leads to damage to the HTS tape and, as a result, the device as a whole.

This problem is studying both theoretical and experimental research groups. In numerical calculations of this process, the final result strongly depends on the choice of the model describing the heat removal of the tape [1]. In a number of works it was shown [2–4] that there is a certain range of currents that exceed the critical value, but less than the limiting current of the thermal transition, in which a stable state is possible if the thermal balance between heat release and heat removal is observed. The article [1] shows that in the presence of a stabilizing layer, the value of the thermal transition of the HTS tape from the resistive to the normal state increases by more than 2 times compared with the corresponding current for the unstabilized tape.

The pulsed current measurement technique (PCM) has been used for a long time for characterizing superconductors at current densities near or above their critical current (Ic), in order to minimize heating effects. Such measurements are of prime importance when considering the optimization of applications
such as superconducting fault current limiters, whose principle of operation is based on the superconducting to normal transition of the superconductor [5]. The results of measurements of the dependence of resistance on current during short current pulses for SuperPower tapes are given in [5, 6]. The effect of short triangular current pulses in the presence of a weak alternating magnetic field on AMSC and SuperPower tapes is described in [7]. The low speed of propagation of the normal zone leads to the occurrence of local overheatings, which destroy the tape, during inhomogeneous quenches. The literature describes ways of dealing with local overheating by increasing the thickness of the stabilizing layer of the tape [8] and by increasing the speed of propagation of the normal zone due to structural changes in the tape [9].

This paper presents experimental data on the study of the influence of stationary and non-stationary current loads with amplitudes far exceeding the critical current, and also examines the effect of initial uniformity of critical current $I_C$-tapes on current load parameters leading to irreversible changes in the transport properties of $I_C$-tapes.

2. Experimental methods

To study the non-stationary processes of degradation of the 2nd generation superconducting tapes, two main methods were used: measuring the current-voltage characteristics of samples in the mode of quasi-stationary flow of the transport current, as well as pulsed flow of current in the subcritical and supercritical modes, as well as local measurements of the spatial distribution of the critical current in the tapes by the method of scanning Hall magnetometry.

2.1. Methods of stationary and non-stationary measurements of the current-voltage characteristic

The well-known and standard approach to measuring the critical current of HTS tapes by the four-contact method was used for the I-V curve measurements. Measurement of the I-V curve in the non-stationary mode required the modification of the test bench for measuring the I-V curves — the setup for the measurement of the I-V curves was supplemented with an oscilloscope. The current source used is Agilent 6671A # J08 (basic configuration, current up to 300 A). If currents greater than 300 A are required, use an Agilent 6680A # J04 source (current up to 1000 A). If a small current step (50 mA resolution) is required, AgilentN5765A source was used. The current in the circuit was determined using the built-in shunt of the source and an Agilent 34401A voltmeter. The voltage and current were measured using a Yokogawa SL1400 oscilloscope with a 701251 module. The module has the following characteristics: the number of channels 2, the maximum measurement rate of 1 Msample/s, the measurement limits of 10mV - 200 V, the noise level of 100 µV.

Both channels of the module were used to perform the measurements. The first channel measured the voltage at the source shunt, the second channel was used to control the voltage at the potential contacts of the sample. Since high-speed ADCs do not have high sensitivity, as well as due to high noise values of the measuring module, measurements were made simultaneously by oscillograph and by more accurate voltmeters of the VAC measurement bench, which allowed us to precise the values of current and voltage on the sample when entering the quasistationary mode after a pulse increase of current.

Measurements were carried out in liquid nitrogen on a specially designed insert for I-V curves measuring. Powerful copper busbars allow a large amplitude current to pass through without significant heating due to layering and efficient cooling with liquid nitrogen. Powerful copper busbars allow a current with large amplitude to pass through without significant heating due to multilayered structure and efficient cooling with liquid nitrogen. Potential contacts are spatially separated from the current supply conductors, which also eliminates the influence of a large amount of current flowing through the buses on the voltage value on potential contacts.

2.2. Methods of local magnetic measurements based on Hall scanning magnetometry

For a more complete analysis of the processes of degradation of 2nd generation HTS tapes, we also used a spatial-sensitive method for studying the local current distribution in a superconductor. Based on the data of the current distribution, it can be concluded that damage occurs in the superconductor and
the local regions with a lower critical current appear. In this case, one of the reasons of the appearance of damaged regions may be thermal instabilities of the superconductor when the transport current passes through the sample, especially in a non-stationary mode.

Scanning Hall magnetometry was used to study the samples. The description of the stand used in the work and the method of restoring the picture of the distribution of currents can be found in the work [10].

The stand allows to obtain primary information about the local magnetic properties of the samples. To obtain information on the current-carrying properties of superconductors, it is necessary to analyze the processes of the occurrence of currents in the sample and the restoration of the current distribution in the superconductor.

Magnetic field scanning is performed in the captured mode. It is necessary to calculate the spatial distribution of the current from the experimentally obtained surface distribution of the magnetic field of the transport current \( B_z(x, y) \). It is necessary to solve the problem of inversion of the Biot-Savart-Laplace equation for this. As a result of the calculations, two-dimensional distributions of the current components are obtained along \( J_x \) and across the tape \( J_y \). If the superconductor is defect-free, then the current flows along straight paths along the sample and at the edges of the tape the current turns, forming a closed loop. However, if regions of inhomogeneity arise, associated, for example, with defects, then the current flows around these regions, and the current component along the ribbon decreases (down to 0) and the component across the tape increases.

2.3. Samples

Two types of samples of CC-tapes were investigated: SuperPower tapes and American Superconductor tapes. SuperPower tapes are 4 mm wide. Substrate - Hastelloy, thickness - 50 microns on each side. The tape has a copper coating with a thickness of about 50 microns thick. The total tape thickness is about 100 microns. Tapes manufactured by American Superconductor are 4.8 mm wide. The substrate is Ni-W, with a thickness of about 50-75 microns. The tape has a copper coating with a total thickness of more than 100 microns. The total thickness of the tape is of the order of 200-250 microns, which is significantly larger than that of SuperPower tapes.

3. Results and discussion

The study of HTS tapes was carried out in three main modes: stationary mode (measurement of current-voltage characteristics, critical current determination), non-stationary mode with current pulses not exceeding 1.3 \( I_c \) samples in samples, non-stationary mode with current pulses not exceeding 2.2 \( I_c \) in samples. Also research on the local current distribution in the samples before and after the onset of degradation in the samples was conducted.

In total, 4 samples of Super Power (SP) and 4 samples of American Superconductor (AMSC) were investigated. The length of all samples was from 5 cm (6 samples) to 7 cm (2 samples).

In the stationary mode, the following characteristic results of measurements of the critical current are observed: SP samples from 97.4 to 100.5 A, AMSC samples from 110.8 to 114.1 A. Also, measurements were taken when the current flow was much higher than the critical current of the samples (up to 3 x times). All tapes showed high stability and stability of characteristics; no changes in properties in the samples were observed. The rate of current rise did not exceed 2 A / s. It should also be noted the greater homogeneity of the SP tapes (3.2–9.8%) with respect to AMSC samples (1.9–15%) prior to the study in non-stationary modes.

Studies in non-stationary regimes have revealed some general patterns of behavior of samples from both manufacturers. The occurrence of thermal instabilities during a pulses of the transport current is more critical, and after removing the current load, the degradation of the properties did not exceed 5% of the initial values. The occurrence of instability appears with a significant delay after the current pulse (from 0.2 to 6 seconds), while there is no direct correlation with the current injection modes. This may be due to the dramatically changing conditions of heat removal in liquid nitrogen. An example of this phenomenon is shown in Figure. 1. The delay in the occurrence of the peak can be explained by the low
velocity of propagation of the normal zone. When a current is introduced, heat is generated, which locally overheats the superconductor. The normal zone arises and begins to grow, which leads to an increase in voltage. On the other hand, heat is removed from the superconductor to the copper layer (and further to nitrogen). After that, the superconductor is cooled and returns to the superconducting state, which leads to a decrease in voltage.

For SP samples, an unstable state occurs when the critical current exceeds more than 1.22. In this case, there is a correlation between the local current-carrying characteristics of the tapes and the threshold current for the occurrence of instabilities. So for the initially more homogeneous tapes, the threshold current is higher. At the same time, the current rise rate is minimal for the sample with the greatest inhomogeneity.

Observed features of the behavior of the samples: the appearance of a double peak voltage on the sample after pulsed current transmission (the second peak is much smaller in amplitude, but longer than the first).

The occurrence of irreversible degradation occurs at amplitudes of 1.4 Ic and the rate of current rise is 2-3 times higher than when reversible instabilities occur. Moreover, for more homogeneous samples, the speed and amplitude are higher than for more defective ones. It should also be noted that degradation occurs locally, while a significant part of the tape does not undergo changes in superconducting characteristics. An example of the distribution of the longitudinal component of the current before and after degradation occurred is shown in Figure 2.

For AMSC samples, an unstable state occurs when the critical current exceeds more than 1.25 times. In this case, no correlation is observed between the local current-carrying characteristics of the tapes and the threshold current for the occurrence of instabilities. So for the initially more homogeneous AMSC tapes, the threshold current is lower.

Observed features of the behavior of the samples: the occurrence of a double peak voltage on the sample after pulsed current transmission (the second peak of the same amplitude) is less common than for samples SP. An example of such heterogeneity is shown in Figure 3.

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Observed features of the behavior of the samples: the occurrence of a double peak voltage on the sample after pulsed current transmission (the second peak of the same amplitude) is less common than for samples SP. An example of such heterogeneity is shown in Figure 3.

The emergence of irreversible degradation occurs at amplitudes from 2 to 2.3 Ic and the rate of current rise is 8-10 times greater than when reversible instabilities occur. Moreover, for more homogeneous samples, the speed and amplitude are higher than for more defective ones. It should also be noted that degradation occurs locally, while a significant part of the tape does not undergo changes in superconducting characteristics. Also on sample AMSC4, irreversible deformation corresponds to a region with a significantly lower critical current.

Figure 2. – The distribution of the longitudinal component of the current through the SuperPower sample 2 a) before the current load and b) after the current load
From the comparison of samples from different manufacturers, it should be noted that AMSC samples are more resistant to the occurrence of both reversible and irreversible instabilities than SP tapes, however, the length of the degradation region of samples differs several times. Differences in the behavior of samples are mainly determined by the difference in the architecture of the tapes and the thickness of the stabilizing layers. The AMSC tapes have a significantly larger thickness of the stabilizing copper layer and substrate, which improves the removal of heat generated in the superconductor when current is ramped. This, in turn, leads to a more rapid cooling of the overheated area after the end of the current pulse. When the critical current is exceeded, the current begins to flow along the copper layer, and the thicker layer in the AMSC tapes has less resistance, and accordingly leads to less heating of the tape. All this leads to a higher stability of the AMSC tapes with respect to the current pulses.

Legend used in the tables:
- \( I_c \) – critical current
- \( I_{ri} \) – current of reversible instability occurrence
- \( V_{ri} \) – rate of transport current rise (occurrence of reversible instability)
- \( I_{ri}/I_c \) – current of reversible instability occurrence normalized on critical current
- \( V_{ri}/I_c \) – rate of transport current rise normalized on critical current (occurrence of reversible instability)
- \( I_{ii} \) – current of irreversible instability occurrence
- \( V_{ii} \) – rate of transport current rise (occurrence of irreversible instability)
- \( I_{ii}/I_c \) – current of irreversible instability occurrence normalized on critical current
- \( V_{ii}/I_c \) – rate of transport current rise normalized on critical current (occurrence of irreversible instability)
Table 1. Research results

| Sample | Ic, A  | Iri, A | Vri, A/s | Iri/I | Vri/I, 1/sec | ii, A/s | Iii/Ic | Vii/Ic, 1/sec | Inhomo geneity, % |
|--------|--------|--------|----------|-------|--------------|--------|--------|--------------|------------------|
| SP1    | 100.5  | -      | -        | -     | -            | -      | -      | -            | 3.61             |
| SP2    | 98.7   | 123.2  | 151.4    | 1.25  | 1.53         | 135.5  | 478.2  | 1.37         | 4.85             |
| SP3    | 97.6   | 122.4  | 153.5    | 1.25  | 1.57         | 142    | 446    | 1.45         | 4.57             |
| SP4    | 97.4   | 118.5  | 166.5    | 1.22  | 1.71         | 133    | 348.6  | 1.37         | 3.58             |
| AMSC1  | 114.1  | -      | -        | -     | -            | -      | -      | -            | 15.14            |
| AMSC2  | 111.4  | 147.3  | 579.9    | 1.32  | 5.21         | 228.9  | 3317   | 2.05         | 29.78            |
| AMSC3  | 111.6  | 139    | 387.1    | 1.25  | 3.47         | 260.5  | 3428   | 2.33         | 30.72            |
| AMSC4  | 110.8  | 148    | 428      | 1.34  | 3.86         | 243.9  | 3387   | 2.2          | 30.57            |

4. Conclusions

Studies of the behavior of HTS tapes in nonstationary current input modes have been conducted: superconductor transition processes to a normal state and processes of degradation and of superconductor burnout at high current input rates have been observed. At current input rates above the threshold value, which is different for tapes of different architectures, thermal instability occurs, which manifests itself in the appearance of a voltage peak with a delay after the current pulse. Summarizing the obtained experimental results, we can conclude that:

1) There is no correlation between the current input modes and the delay time of the voltage peak and duration of the peak.

2) The rate of rise and amplitude of the current causing irreversible degradation is higher for more homogeneous samples than for more defective ones, for all types of samples. At the same time, the correlation between the rate of current rise and homogeneity across the tape does not have a general pattern for different types of samples.

3) The degradation of samples occurs locally and most of the sample does not undergo changes in superconducting characteristics.

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