GdBCO (123) HTS 2G tapes superconducting characteristics investigation under the pulsed electron beam exposure impact

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Abstract. The 2nd generation composite HTS tapes samples based on the GdBCO (123) compound were irradiated in a pulsed electron accelerator (Terek-2 facility, IOF RAS) through a tantalum target to determine the thermal and shock loads effect at the tantalum-HTS boundary on the HTS tapes superconducting characteristics. Scanning Hall magnetometry was used to characterize the HTS samples after the electron irradiation exposure. The thermal modes and shock load in a composite superconductor under the irradiation influence are estimated depending on the magnitude of energy contribution to the target. At a silver surface temperature equal to the melting temperature, the critical current value drops by 87% of the initial value. At lower energy, a weaker critical current decrease was observed. The temperature effects and shock waves roles under the irradiation is discussed.

1. Introduction

Currently, superconducting wires (HTS-2) production technologies and physical parameters have reached the level at which the unique devices engineering development, mechanisms and machines for use in space and aerospace fields and in nuclear physics has begun. This is about the energy storage devices, electric motors, powerful magnetic systems. Under operating conditions, HTS can be exposed to various external factors, such as ionizing radiation, shock waves, high temperatures, etc., which will affect the superconductors functional parameters. Therefore, extreme impacts are simulated in the laboratories, allowing to get an idea of the HTS-2 viability under these conditions.

In the literature there are a large number of works on the superconductivity under the ionizing radiation conditions study. The results show that in certain cases the critical current increasing effect as the radiation defects creation result - the Abrikosov vortices pinning centers was observed. This was previously discovered for the Nb₃Sn superconducting compound (see, for example, [1, 2]). Also, in the HTS cuprates, the critical parameters improvement was obtained under the various nature ionizing particles irradiation influence (for example, [3-6]).

In addition, the superconductors critical parameters improvement under the shock waves action due to the more equilibrium structural phase states creation and the dislocation interstitial loops and vacancy pores - pinning centers - formation was discovered in [7, 8].

This work is devoted to the superconducting properties changes study of HTS-2 tapes samples based on the GdBa₂Cu₃O₇₋ₓ compound upon the relativistic electron beam (REB) irradiation in the Terek-2 facility.
2. Experimental methods

The Terek-2 experimental installation is the pulse electron accelerator with the pulse current magnitude up to 10 kA and the pulse duration up to 35 ns. The beam electron energy can be continuously adjusted in the range from 200 to 550 keV. The accelerator used a storage capacity (2.5 μF, 50 kV) as a charger, which is discharged through a pulse autotransformer to a double forming line. As a result, a trapezoidal high-voltage pulse is generated in the gap between the anode and cathode, resulting in the high-energy electron current pulse appearance due to cathode explosive emission.

The sample irradiation scheme is shown in figure 1. To avoid the direct electron beam action on the superconductor, a tantalum target 12×12 mm² in size and 0.1 mm thick was placed in front of the sample, to the back side of which the HTS sample was glued. Exposure modes are given in the table 1.

![Diagram of exposure geometry](image)

**Table 1.** Electron beam modes in the experiment on the HTS samples irradiation and temperature in the energy input region and the relative change in the critical current compared to the initial value at various values of the REB

| Sample number | 1   | 2   | 3   | 4   | 5   | 6   |
|---------------|-----|-----|-----|-----|-----|-----|
| $E_e$, keV    | 460 | 430 | 410 | 480 | 460 | 460 |
| $I_{max}$, kA | 2.6 | 4.0 | 1.8 | 0.9 | 0.8 | 0.5 |
| $j_{max}$, kA/cm² | 8.7 | 13.3 | 6.0 | 3.0 | 2.7 | 1.7 |
| $E_{nucle}$, J | 42  | 60  | 26  | 15  | 13  | 8   |
| Temperature, K | 1703 | 1233 | 973 | 629 | 568 | 479 |
| $I_c/I_{c0}$  | 0.16 | 0.56 | 0.95 | 1   | 1   | 1   |

As samples, the segments of HTS-2 tapes based on the GdBCO (123) compound measuring 12×12×0,1 mm³ manufactured by SuperOx were used. HTS-2 tapes are multilayer composites with the following technical characteristics: critical temperature is 93 K, critical current density at $T=77K$ $j_c=2\times10^6$ A/cm²[9]. The composite tape architecture is shown in the figure 2. Buffer layers of La₂O₃, MgO, Y₂O₃, Al₂O₃ with a 200-300 nm total thickness were deposited on a Hastelloy C276 substrate with a thickness of 100 μm, onto which a 1-μm GdBCO (123) layer was deposited by laser sputtering, and a 2-μm Ag layer was deposited on top.
The critical temperature was measured before and after irradiation with direct current using the four-probe method.

To study the HTS tape critical current spatial distribution after the REB action, the scanning Hall magnetometry method was used. An automated experimental bench was used, which included a three-coordinate system for moving the sensor and permanent magnets for the superconductor magnetization. The sample, previously cooled in liquid nitrogen, passes in the gap between two closed permanent magnets, while in the superconducting layer shielding superconducting currents are created. Using the Hall sensor, a trapped magnetic field above the sample is scanned; the measurement height is 0.5 mm. A Hall transducer with the following characteristics was used: transducer size - 2×1.5×0.6 mm³, sensor working area size 0.45×0.15 mm², magnetic sensitivity is 94 μV / mT. From the obtained two-dimensional magnetic field $B_z$ normal component distribution, by solving the inversion of the Biot-Savart law in the Bean model framework, the critical current and the local distribution of the current components along and across the sample were determined [10-12]. A conclusion about the local changes in the HTS tapes samples current-carrying characteristics is proposed based on the presence of current domains and their topology. In a first approximation, $I_c \sim \text{grad } B_z$.

3. Experimental results

The measuring results of the trapped magnetic flux induction $B_z$ by the Hall scanning magnetometry are shown in the figure 3 (a, b, c, d) for the original and three irradiated samples.

As can be seen from the illustrations, in the case of sample №1 ($E=42$ J), the distribution uniformity corresponds to the original sample, but the current amplitude is 1.8 times less than the initial one. For the sample №3 ($E=26$ J), the distribution uniformity corresponds to the original sample. The current amplitude is 5.5% less than the initial one. In the case of the sample №2 ($E=60$ J), figure 3d, the tantalum target was severely deformed and pierced. The sample №2 has a significant current heterogeneity with respect to the original sample. The middle part (presumably the shock region) - only focal superconducting sections remain, the current closures along the sample edges correspond the original sample. The current amplitude is the 6 times less than for the initial sample. In all other cases (samples №№ 4, 5, 6) no effect on superconductivity was found. The electron beam energy is too low.
Figure 3. Normal component $B_z$ of the trapped magnetic field distribution in the a-original SuperOx tape sample, b-sample of SuperOx tape №1 (after irradiation), c-sample of SuperOx tape №3 (after irradiation), d-sample of SuperOx tape №2 (after irradiation).

Figure 4 shows the critical current temperature dependence on the Ta-Ag section boundary. This dependence, perhaps, will explain the superconducting state suppression mechanism in this experiment.

Figure 4. Dependence of the critical current $I_c$ on the temperature at the tantalum target – HTS boundary. $I_{c0}$ and $I_c$ were measured at $T = 77$ K and $B = 0$. 
4. Heat processes calculation

To explain the obtained experimental results, the thermal and shock wave processes occurring in the material under study — a composite superconductor — as a result of irradiation of a tantalum target with a relativistic electron beam were evaluated.

As can be seen from the Table 1, six samples with different energy input levels from 8 to 60 J were exposed. Since the tantalum foil 100 μm thick was directly exposed to the electron beam, the pressure and temperature perturbation on the HTS was determined by the temperature and pressure on the external side of the foil respected to electron beam (figure 1). As a result of irradiation of the sample № 2 \((E = 60 \text{ J})\), the outer side of the tantalum target was strongly deformed and melted. The sample itself underwent mechanical damage with traces of silver melt. When the beam energy level was reduced to \(E = 42 \text{ J} \) and lower, mechanical damage to HTS samples (№ 1, 3, 4, 5, 6) and tantalum foil were not observed.

To assess the temperature effect at the Ta-foil-silver section boundary on the HTS samples superconducting characteristics, the energy deposition in the region of interaction between the electron beam and the tantalum target was estimate. When a target is irradiated with an electron beam, the part of the electron beam is reflected from the target. The fraction of reflected electrons and the energy carried away by them weakly depend on the beam initial energy, and is determined only by the target material core charge \(Z\). For the tantalum, this value is \(\sim 40\%\) [13]. Other beam energy loss types \((0 < E < 2.5 \text{ MeV})\) upon the metal targets irradiation do not exceed 1-3%. Thus, \(\sim 50\%\) of the beam energy is used to heat the interaction region of electron beam with the tantalum target.

The temperature value on the tantalum foil outer surface is estimated at the beam energies given in the Table 1, based on the simplest model concepts. First of all, we assume that the substance (Ta) absorbing the energy of the beam can be considered locally equilibrium during the current pulse. An increase in internal energy causes only the temperature increase, and the processes of heat and mass transfer can be neglected [14]. The energy release zone temperature expression in this case is:

\[
T(r, t) = \frac{D(r, t)}{c(T)\rho(r)} n(r, \Delta t) + T_0(r, t)
\]

where \(c(T)\) - specific heat, \(\rho\) – tantalum density, \(n(r, \Delta t)\)– beam electron density, \(D(r, t)\) – fraction of energy lost by the electron during braking in the foil, \(T_0(r, t)\)– tantalum temperature before the REB exposure. Formula (1) can be represented as:

\[
T(r, t) = \frac{0.5E}{c(T)\rho(r)\nu(t)} + T_0(r, t),
\]

where \(E\) – beam energy, \(V = R_e \times S_c\)– energy zone volume, \(R_e\) - extrapolated 460 keV electron range in tantalum foil, \(S_c\)– beam cross-sectional area.

To determine the tantalum target temperature depending on the beam energy, we determine the electron beam energy deposition region volume \(V\) in the Ta foil at the end of the REB pulse (beam energy 60 J, \(\tau \sim 35 \text{ ns}\)).

It is known that the extrapolated electrons range in a substance with a charge \(Z\) and mass number \(A\) is related to the range in aluminum as follows [15]:

\[
R_E(A, Z) = R_E(Al) \left(\frac{Z}{A}\right)^{1.4}_{\text{Al}} \left(\frac{Z}{A}\right)_{Ta}
\]

where \(R_E(Al) = 0.4 \cdot E^{1.4}\) at \(E < 0.8 \text{ MeV}\), \((Z/A)_{Al} \approx 10^{-4}\), \((Z/A)_{Ta} \approx 1\) (\(Z\)– charge number, \(A\)- mass number) of the aluminum and tantalum, \(C(T) = 0.151 \text{ kJ} / (\text{kg} \cdot \text{K})\), \(\rho = 16600 \text{ kg/m}^3\), \(T_m = 2996 \text{ °C}\).

As follows from the experimental results, at the beam electron energy of 42 J, no visible changes in the silver insert surface structure occur, while at the energy of 60 J there are foci of molten silver. We assume that at the energy of 42 J, the temperature is \(\sim T_m\) of silver at the Ta – Ag boundary. Then from
(2) the volume of the energy input region can be determined. The volume of the energy input region of the electron beam is \( \sim 1.0 \times 10^{-8} \) m³.

With the beam energy change, the energy deposition region volume remains practically unchanged (electron energy \( \sim 460 \) keV). With this in mind, substituting the corresponding values of the beam energy in the equation (2), we obtain the temperature in the energy input for various beam energy values (table 1, two last lines).

The tantalum foil irradiation by a REB pulse leads to the pressure increase that arises in the heated zone immediately after the electron beam energy absorption, which can lead to the shock wave (SW) formation. The criterion for the SW formation [16] has the form:

\[
\frac{E}{\tau^2} > c^4_L \rho
\]

where \( E \) - total absorbed pulse energy with a duration \( \tau \), \( c_L \) - longitudinal sound velocity in Ta, \( \rho \) - tantalum density. Inequality (4) in our case does not hold (\( Q \ll c^4_L \rho_0 \tau^2 \)).

High-energy beam tantalum target irradiation—electrons with the energy of (8-60) J in the circuit shown in the figure 1, leads to heating of the Ta-Ag interface from 450 K to 3000 K. The shock wave with such energy depositions in the Ta target does not form.

5. Conclusions

Therefore, estimation presents that the HTS tape samples irradiation through 100 μs tantalum target with REB pulses with an energy depositon(contribution) of 42 J and 26 J leads to small thermal disturbances, as a result of which the critical current decreases by about 50% and 5.5%, respectively. REB with 60 J energy leads to a significant (6 time) critical current decrease and mechanical damage to the tape sample. Calculations show that the critical current dependence on the REB energy contribution (figure 4) gives reason to consider that the observed changes are associated only with thermal and not shock-wave factors.

The critical current decrease by the REB influence may be due to the transition of the orthorhombic superconducting phase to the tetragonal nonsuperconducting one. This structural phase transition for YBCO (123) occurs at a temperature \( T_p \approx 1000 \) K [17]. We assume that in GdBCO (123) \( T_p \) has the same value. With an energy input increase the fraction of the superconducting phase decreases, which leads to a decrease in the critical current value (figures. 3, 4).

Acknowledgments

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