Investigation of the hysteresis losses in CC tapes after laser filamentation

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Abstract. Study of AC loss has been conducted on the 4 mm wide CC-tapes manufactured by SuperOx. Filamentation was carried out by laser cutting of the commercially available tapes with a copper coating. Also for comparison, original tapes and commercial multifilament tapes (manufactured by SuperOx by using chemical etching method) were studied. Losses were obtained from the magnetization curves measured on a vibration sample magnetometer in the temperature range from 4 K to 77 K. In addition, the current carrying characteristics of tapes were studied, and the effect of filamentation on the critical current value were examined. We present an analysis of the experimental results, as well as a comparison of data for different types of samples. The possibility of decreasing the energy losses due to filamentation tapes was demonstrated.

1. Introduction
Due to the extensive development of high-temperature superconductivity important task of the efficient use of HTS materials in the energy sector is a problem of reducing the alternating current energy losses in coated conductors tapes (CC-tapes). This problem can be solved by various methods. So, to reduce the losses one can use a special laying method in the cable [1], [2]. Work [3] presents the effect of the tape size and the distance between the individual layers on the losses. The calculation results indicate low expediency of using tapes less than 4 mm width. Thus, it is necessary to develop methods to reduce AC losses for CC-tapes with optimal width.

There are several basic approaches, one of which is based on the separation of the HTS layer into several filaments. Multi-filamentation of the CC-tape can be performed in various ways. For example, work [4] presents the filamentation technique with additional virtual cross-section of the buffer layer. Filamentation can also be performed by the deformation, partial removal of the buffer layer [5], or coating of buffer layer with nanolayer [6]. All this leads to disruption of the superconductor structure above the modified part of the buffer layer. Filamentation can be performed without modification of the substrate or buffer layer. In particular, in work [8] authors proposed a method for producing CC-tape with a zigzag pattern of filaments obtained using the three-step photolithography and chemical etching. The tape filamentation can be done, for example, by laser irradiation of the CC-tapes with

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copper coating [9]. This approach is relatively simple since only the post-processing of finished CC-
tape is required.

Work [10] describes a complex method of filamentation, leading to record level of AC losses
reduction. Non-stabilazed tape was annealed in oxygen after the filamentation process, which leads to
oxidation of the buffer layer between the adjacent filaments and isolates them from each other.

Among the methods described above the laser filamentation of copper coated tapes is one of the
most promising due to its simplicity and scalability. Also, this technique allows one to tune
filamentation parameters for specific tasks.

2. Experimental technique and discussion

2.1. Samples
In our study we used commercially available 4 mm width GdBCO tapes manufactured by SuperOx.
The tapes of 0.11 mm thickness on Hastelloy C276 substrate had no isolation. They were copper
coated with 50 microns plating thickness. The critical current was about 150 A. The tapes were
filamented using laser cutting technique. In addition, we investigated SuperOx produced tapes without
copper coating which were divided into 4 filaments by chemical etching.

2.2. Laser specification.
The tapes were divided into four filament by laser cutting performed using ytterbium pulsed fiber laser
with 1.068 micron wavelength and 50 microns focus diameter. Maximal power per pulse of 1 mJ,
pulse frequency range from 20 to 100 kHz and beam moving speed up to 20,000 mm/sec and were
used.

2.3. Selection of a laser power
We used four-probe method for critical current measurements and the scanning Hall magnetometry to
assess the impact of laser radiation on the superconducting layer. To obtain the laser parameters
suitable for the filamentation, the tapes were cut in transverse direction and the critical current was
measured. The dependence of the critical current on the laser incision parameters is shown in Figure 1.
As a result, we picked up minimal energy of laser pulse, which destroys superconducting layer and
provides minimal substrate damage and distortion of the tape.

To check the quality of the laser cut we used a home-made Hall magnetometer [11]. After the laser
cutting (the pulse energy 1 mJ, the pulse frequency 20 kHz, the beam moving speed 50 mm/s.) the
sample was cooled in liquid nitrogen and magnetized using permanent magnets. Then the picture of
remanent flux was measured (Figure 2) and converted into a current distribution by inversing of Biot–
Savart equation (Figure 3). Laser cut is clearly visible in Figure 3. There is no current flow through the
cut.

2.4. Multifilamentization technique.
After the laser parameters were selected, tape was filamented into 4 stripes. To estimate the
filamentation effect, the direct measurements of the critical current was carried out for both non-
filamented and filamented tapes. The tapes chemically filamented by SuperOx were also measured
for comparison. The critical current decreased from 150 A to 140 A under the laser filamentation.
Such weak decrease (less than 10%) indicates a small cutting width leading to small change of the
superconductor cross-section. The critical current of chemically filamented tape dropped to 40 A.
Figure 1. The dependence of the critical current obtained after the laser incision on the laser pulse energy. The pulse frequency - 20 kHz, the beam moving speed - 50 mm/sec.

Figure 2. Distribution of the trapped field near the transverse cut at temperature $T = 77$ K.

Figure 3. Calculated current distribution near the transverse cut at temperature $T = 77$ K.

Figure 4. An example of the magnetization curve for all three samples at $T = 50$ K.

Figure 5. Dependence of the relative losses on the integration region at $T = 50$ K.
Figure 6. Temperature dependence of the relative losses normalized by the relative change of critical current. Data are presented for the integration region of 0.6 T. Normalization factors are 140/150 and 40/150 respectively for laser and chemically filamented tapes.

On the next step we studied filamentation influence on AC losses estimated as hysteretic losses per cycle multiplied by operating frequency. The hysteretic losses were evaluated from the magnetization curves measured on a vibration magnetometer at various temperatures in external magnetic field produced by 15 T superconducting magnet Oxford Instruments. Measurements were performed with sweep rate of 0.5 T/min. Each curve was measured from zero field up to 2 T, then to -2 T and again to zero. The curves obtained at $T = 50$ K are shown in Figure 4 as an example. Hysteretic losses per cycle can be evaluated according to the formula:

$$P_h = C \times A \times \mu_0 \times \oint H_e dM = -C \times A \times \mu_0 \times \oint M dH_e$$

where $H_e$ – is applied magnetic field, $M$ - magnetization, $C \times A$ - the effective cross section of the superconductor, $A$ represents a geometric section, and $C$ - the effective coefficient, at a low frequency $C = 1$ [12]. The region of integration is chosen the same as an amplitude of the external field affecting the superconductor (or tape self-field, in the case of AC current loss in zero external field). The hysteretic losses calculated for several fields from the magnetization curves presented in Figure 4 are shown in Figure 5. The losses of filamented tapes were normalized to the losses of the non-filamented one. The relative losses of two samples with identical sizes can be obtained as the ratio of their hysteresis loops areas. So, there is no need to calculate the coefficients before the integral. Example of dependence of the relative losses on the field amplitude for the temperature $T = 50$ K is shown in Figure 5. The graph shows the losses reduction for both types of filamentation, in comparison with the non-filamented tape. We obtained that the losses increase with field, therefore in low fields, or in self-field for AC current, the filamentation is more efficient.

Due to the differences of the critical currents of the laser and is chemically filamented tapes, it makes sense to normalize losses on the relative change of critical current caused by the filamentation procedure. Normalization factors are 140/150 and 40/150 respectively for laser and chemically filamented tapes. Figure 6 shows the normalized loss as function of temperature. This dependence shows that the relative losses of sample filamented by laser less than the losses of the chemically filamented sample. In addition, for both samples the relative losses tend to decline at higher temperatures. The only exception is the point at $T = 50$ K for the chemically filamented sample for which the loss growth can be attributed to the error of the experiment.

3. Conclusion
Effect of laser filamentation on hysteretic losses in CC-tapes was studied. Optimal parameters of laser cutting of tapes with copper coating were chosen experimentally. Measurements of hysteretic losses per cycle demonstrated the possibility of AC losses reducing via tapes filamentation.

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