Study of HTS Conductors Made From Combinations of HTS Tapes

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Abstract. To increase current carrying capacity of an HTS conductor we combined two HTS tapes by soldering or packaging. It permitted to increase current carrying capacity of conductors, while not exactly proportional to the number of tapes used. Slight critical currents reduction is more pronounced for the magnetic fields parallel to the tape’s surface due to induced current loops. Affect of the self field on critical currents is more pronounced when perpendicular external fields are applied. Complicated current transfer between tapes has been observed and should be taken into account during characterization of combined tapes.

1. Introduction

First generation Bi-based HTS-tapes currently available on the market have critical current at 77 K in the self-field from 40 A to 150A per single tape. The critical current reduces noticeably with magnetic field applied to tapes what is essential for most application. On the other hand, many applications (HTS-transformers, FCL, cables, magnets, etc.) may need an HTS conductor with critical currents of several hundred amperes and more. Thus, it is necessary to combine several parallel HTS tapes to make current carrying element with high critical current.

Like for low-Tc superconductors, some factors are influencing on the current carrying capacity of the combined conductor from parallel tapes or current carrying elements (CCE). These factors make the critical current of CCE less than sum of critical currents of the basic tapes. The study of these factors has practical importance to develop combined conductor with high critical current.

In this paper we present CCE made from two HTS tapes by two methods. We determined problems that may reduce the critical current of CCE and discussed them. We also discussed what experimental peculiarities should be taken into account during characterization of CCE.

2. Experiment

The basic tapes we used to produce CCE are listed in the Table 1. Three CCE (#1, #2 and #4) were made from tapes without reinforcing and one from the stainless steel reinforced tapes (#3). The stainless steel reinforced tapes at CCE were combined together by packing them inside the round braid from thin copper wires. The tapes without reinforcing were soldered with standard PbSn solder.

We prepared combined conductors with different lengths to study the influence of the length on the current carrying capacity of samples. Most samples have lengths ~18 cm and ~48cm and one of the samples from tape #3 has the length about 1.5 m. The shorter samples were tested as the straight strips...
on the inserts placed to the split copper coil, which generated up to 0.2 T magnetic fields over the length ~4-5 cm.

| Samples / Producer                      | Sizes of the tape mm × mm | CCE prepared                                |
|-----------------------------------------|---------------------------|---------------------------------------------|
| #1 / AMSC (USA)                         | 0.24 × 4.0                | Two tapes soldered                           |
| #2 / InnoST (China)                     | 0.23 × 4.2                | Two tapes soldered                           |
| #3 - Stainless steel reinforced / AMSC (USA) | 0.31 × 4.1                | Two tapes non-soldered packed with the braid |
| #4 / Sumitomo (Japan)                   | 0.22 × 4.3                | Two tapes soldered                           |

**Figure 1.** The sketch of a CCE sample with potential taps attached. Not in scale. Thick arrows show the current transfer way.

The sketch of the straight sample on the sample holder is shown in Figure 1 with potential taps shown. The number of potential taps attached permitted us to measure voltages along each tape and in the transversal directions. It also permitted to measure potentials on top and bottom of CCE tapes separately, to investigate current transfer between tapes. For more detailed study of the current transfer between tapes, the top tape has been shortened by partial cutting beyond current leads as it is shown in Figure 2. All tests were performed at liquid nitrogen temperature. V-I characteristics from different pairs of potential taps were measured at the constant magnetic fields when current was slowly raised. 1μV/cm criteria was used for definition of the critical current.

**3. The experimental results and discussion**

3.1. Current carrying capacity.

In Figure 3 the dependencies \( i(B)=I_c(B)/I_{c(B=0)} \) for all CCE are shown for perpendicular and parallel to the tape surface magnetic field orientations. Critical currents in perpendicular magnetic fields practically do not depend on length of the samples and methods of combining tapes. They are close, but slightly less than the doubled current of the single tape. In the parallel magnetic field the critical current reduction is more pronounced. Noticeable scattering of critical currents was observed for samples with higher transversal resistances (see, for example sample #3 in Figure3).

Most probable reasons to cause the critical current reduction are self field phenomena. The scattering of the critical currents could be caused by induced current loops. We discuss this in the next section.

3.2. Time depended induced currents

The induced currents are the common phenomenon for multi-strand or combined superconductors. Induced currents can be determined from the local magnetic fields measured by Hall Sensors (HS) [1]. We performed such measurements. The location of sensors is shown in Figure 4. One can see that all components of the magnetic fields may be measured with such arrangements. We made an attempt to evaluate induced currents appeared after transport current ramped up to 20-120 A and then dropping
currents to zero. Measurements at zero current permitted us to exclude the signals from magnetic field of the transport current. The results obtained may be summarized as follows:

- After current ramp up and then down to zero all HS signals did not returned to zero level and demonstrated slowly changes from some initial, non-zero level. Time constants of changes are very long; they were estimated as at least $10^2$-$10^4$ s for soldered samples.
- If the sample was warming up above 100 K the HS signals were going exactly to their initial zero values.
- The magnitudes of remaining HS signals depend on prehistory of ramping and are not exactly reproducible.

The data obtained from HS showed that change of the transport currents leads to the induced currents inside the CCE that decay with very long time constant. It is quite similar to the phenomena observed in multi – strand low $T_c$ cables [1, 2]. The magnitude of HS signals permitted us to estimate the magnitude of the induced currents. Our evaluations from measurements by HS – B showed that up to 20-30% of the ramped current could be added to the transport current in the parallel magnetic field. It causes the observed reduction of the critical current of combined conductors.

We evaluated the combined affect from self field and induced currents. It is shown in Figure 3 by dashed lines. One can see good coincidence of calculated and experimental data. Therefore, both: induced currents and self field may be responsible for critical current reduction in combined tapes. Self field influence is more sounding in perpendicular fields. Induced currents are more important in parallel fields. Dependence of induced currents on prehistory also explains observed scattering of

**Figure 3 (above).** Relative critical currents at two orientations of magnetic fields for single tapes (solid lines) and double tapes (symbols). Different symbols mean different lengths of the test samples. Triangles ~48 cm and 1.5 m for the tape #3, circles and boxes (both open and closed) ~ 18 cm. Dashed lines – estimation of the critical current reduction due to the self field influence and due to induced current loops.

**Figure 4 (left).** Hall sensors arrangement to measure the time-dependent changes of local magnetic field.
critical currents in parallel fields. To obtain more reproducible data in parallel fields it is useful to warm up combined conductor after each measurement.

3.3. Current transfer between tapes.

In Figure 5 the typical V-I characteristics for the soldered sample are shown at zero magnetic field. Measurements were done with two different pairs of potential taps – on the top and on the bottom of the sample (see Figure1). One can see that while bottom potential taps show usual behavior for voltage – current characteristics, the top potentials demonstrate some initial potential.

This additionally appeared potential is connected with the current transfer between tapes. To demonstrate it we shortened the top tape beyond current leads as it is shown in Figure 2. In this case, the current first go to the bottom tape and then to the top tape. Corresponding V-I characteristics are shown in Figure 6. One can see that current first is transferring to the bottom tape that is directly connected to the current leads. When the current reach ~100 A (about \( I_c \) of one tape) the current starts to transfer to the top tape and the transversal potentials appear. As the total transport current reaches ~200 A, the potential appears on the top tape. It means that in both tapes the currents reached their critical values.

The longitudinal voltage behavior shown in Figure 6 is similar to those shown in Figure 5 if to swap top and bottom tapes. The appearance of the small potential at low currents means that during CCE energizing, the current first flow to the better connected tape (the top tape in Figure 6 and the bottom tape in Figure 5) and only then go to other tape. This phenomenon should be taken into account in determining of the critical current magnitude. Improper location of potential taps may lead to wrong measurements and provide confusing results.

4. Conclusions

The combining of two HTS tapes with two different methods demonstrated the feasibility to obtain tentative doubling of the critical current in CCE. The critical current degradation is connected with two reasons: the self field influence and the extra currents from induced current loops during current change. Irreproducibility of induced current loops leads to scattering of the \( I_c \) data in parallel magnetic fields. It is more pronounced in samples with higher transversal resistance. The current loops have long time constants and this limits AC use of the CCE tested. During characterization of CCE the proper location of potential taps is important because of complicated current transfer between tapes during energizing. The technology of HTS CCE prepared by soldering or packaging could be recommended for HTS DC applications where currents more than in a single HTS tape are necessary.

References
[1] Vysotsky V S, Takayasu M, Minervini J M et al 1995 IEEE Trans. Appl. Supercond. 5 580
[2] Balsamo E P, Gislon P, Pasotti G, et al 2000 IEEE Trans. on Appl. Supercond., 10 1598