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Electromagnetic properties of REBaCuO superconducting tapes considered for magnets of fusion reactors

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The RE-123 tapes represent the most advanced product in the field of high temperature superconductors, developed for transport of high electric currents. Although this product has already proceeded to the stage of industrial production, the variety in approaches employed by different manufacturers make the final products by far not identical. We studied electromagnetic properties of a series of tapes delivered by main global wire manufacturers. The tapes were tested by magnetic induction technique (vibrating sample magnetometer) and by current transport. The aim was to find the best candidates for wiring superconducting magnets for fusion reactors. Engineering currents were deduced from magnetic hysteresis loops measured by vibrating sample magnetometer (VSM) at several temperatures. These data were compared with the results of direct transport experiments. The VSM tests were repeated after neutron irradiation of the tapes by neutron fluence of 2.12 E18 cm^{-2}. A significant enhancement of engineering currents was observed in magnetic fields above 0.5 Tesla in all investigated tapes. The enhancement, similarly as the engineering current, was roughly exponential function of temperature.

Keywords: superconducting REBaCuO tapes; magnetic hysteresis loops; transport currents; engineering currents; angular dependence; neutron irradiation.

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1. Introduction

A huge effort has been recently devoted worldwide to development of a new generation of high temperature epitaxial superconducting $REBa_2Cu_3O_y$ (REBaCuO, RE-123, RE=rare earth, usually Y or Gd) tapes prepared on metallic substrates. RE-123 is characterized by rather high critical current densities up to vicinity of the critical temperature (typically above 90 K) and by a high upper critical field. The critical currents are particularly high just in thin films. However, the current density rather quickly drops with increasing film thickness [1,2], which goes against the need of rather thick tapes for transfer of high currents. The superconducting layers require a suitable adaptation to the substrate – several buffer layers properly textured need to be used [3]. All the endeavor has led to development of the "second generation", "coated conductor" tapes offered nowadays by several manufacturers on the market, in lengths up to 1.5 km, allowing construction of high-field magnetic coils [4-6]. While the basic characteristics are usually provided by manufacturers, some special applications, like use in magnets for fusion reactors, where neutron irradiation acts [7,8], require an extended characterization.

In the present paper we bring a survey of engineering currents reached in a series of 21 tapes from three manufacturers, tested by inductive and transport techniques. The angular dependence of transport currents is provided and the first results of our study of the effect of neutron irradiation on the currents are shown.

2. Experimental details

Twenty one REBaCuO tapes were collected for the present study, thirteen samples of SuNAM, seven tapes of SuperPower and one of SuperOx. The SuNAM tapes, all reactively co-evaporated $GdBa_2Cu_3O_y$ thick films, formed three groups with different protective sheaths: the tapes denoted A1-A4 were single-side silver-capped Ag/ GdBCO/LMO/MgO/Y_2O_3/Al_2O_3/substrate, those denoted B1-B4 were surround brass-laminated solder/brass/ solder/Cu/Ag/GdBCO/LMO/MgO/Y_2O_3/Al_2O_3/substrate/ Cu/solder/brass/solder, and the C1-C4 tapes were both-side copper plated Cu/Ag/GdBCO/LMO/MgO/Y_2O_3/ Al_2O_3/ substrate/Cu. In each group, two samples were prepared on Hastelloy substrate and two on a nonmagnetic stainless steel STS310S substrate. The Hastelloy substrate was 63 µm thick, the stainless steel was 104 µm thick. One SuNaM sample had no detailed identification. All 7 samples of SuperPower are YBCO tapes prepared on a stack of buffer layers deposited on a 50 µm thick Hastelloy® C-276 substrate and surrounded by copper stabilizer, type SCS. Two samples, with a "normal pinning", SCS4050, were cut from the same tape 4 mm wide. Five samples were denoted by manufacturer as "advanced pinning, AP" ones, one of them being doped by 7,5% Zr, one by 15% Zr and three un-doped. One of the latter tapes was 3 mm wide, two other were 4 mm wide. One sample was delivered by Prof. M. Gryaznevich without a closer description. According to its electromagnetic and pinning performance, the sample was identified as SuperPower 4050AP. Some details of the tape technology related to SuperPower samples can be found e.g. in Refs. [3,9].

The Russian company SuperOx announces on its web site that they use ion-beam assisted deposition for buffer layers, the pulse laser deposition for some buffer layers and for the superconducting film, and the substrate is Hastelloy® C-276. No further details on the tape technology are known to us at the moment.

As regards measurements, most of the experiments were performed using a vibrating sample magnetometer by which we measured magnetic hysteresis loops at 10 K, 50 K and 77 K with magnetic field sweep rate of 0.7 T/min and magnetic field aligned with the tape normal. These measurements were done on samples 1.5 x 1.5 mm^2 cut from the middle of each tape using a wire-cut EDM (electrical discharge machining). Current density (in A/m^2) was calculated from the MHL height using the extended Bean formula for rectangular samples,

$$J_c = \frac{2\Delta m}{a^2 bc\left(1-\frac{a}{3b}\right)} \quad , \qquad (1)$$

where Δm is the MHL height (in emu), a and b are the sample dimensions (in m) transversal to the field direction, $a \leq b$, and c is the sample thickness. The engineering current $I_c = 4cJ_c$ was calculated considering the superconducting layer 4 mm wide, of thickness c. The inductively accessed current values were compared with the transport current data. The transport measurements were provided by our colleagues from the Institute of Electrical Engineering, SAS, Bratislava. Their facility allowed to measure the transport currents on the original tapes up to 4 cm long at 77 K and in magnetic field up to 1 Tesla. The tape could be measured at an arbitrary angle of magnetic field with respect to the tape plane, giving us an opportunity to measure the angular dependence of the transport currents.

Ten representative samples were then irradiated by neutron fluence of 2.12E22 m^{-2} in the LVR-15 fission reactor of the Research Centre Rez and after the samples' irradiation level decay to allowable value the effect of irradiation on the I_c values was inductively measured by means of VSM.

3. Experimental results

The typical magnetic hysteresis loops observed on ReBCO tapes prepared on Hastelloy substrates are shown in Fig. 1. They exhibited a single peak at self-field and

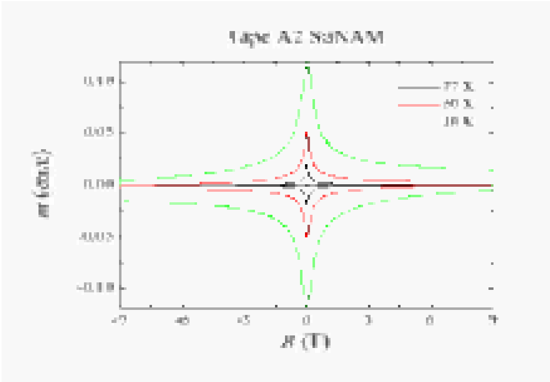


Fig. 1. Magnetic hysteresis loops of the SuNAM sample A2 (GdBaCuO, Hastelloy substrate, single-side silver-coated) measured by VSM at three indicated temperatures.

magnetic moment continuously decreased with increasing magnetic field. There was only a weak paramagnetic background. Some SuNAM tapes exhibited a more complicated background, with a weak ferromagnetic component, as shown in Fig. 2.

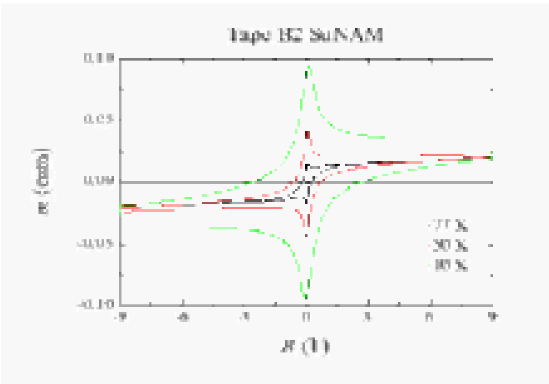


Fig. 2. Magnetic hysteresis loops of the SuNAM sample B2 (GdBaCuO, Hastelloy substrate, surround brass laminated) measured by VSM at three indicated temperatures.

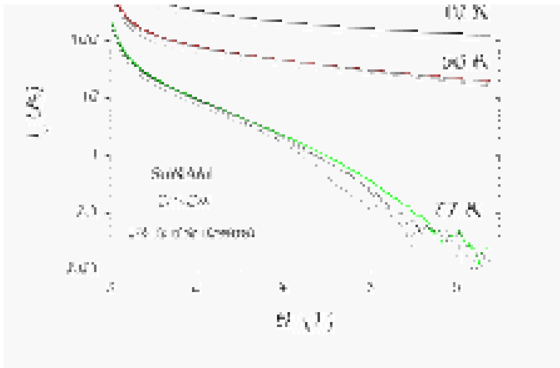


Fig. 3. Engineering currents as a function of magnetic field of the SuNAM samples C1-C4 (GdBaCuO, Hastelloy and stainless steel substrates, copper laminated) deduced from VSM data for three indicated temperatures.

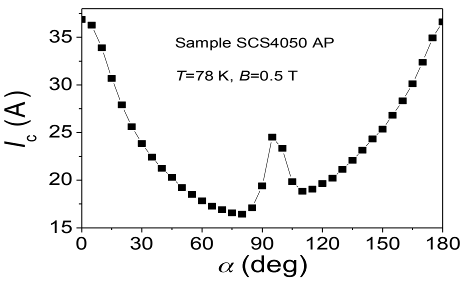
The engineering currents calculated from MHLs by means of Eq. (1) for the tape cross section 4c mm^2 are for C1-C4 tapes of SuNAM plotted in Fig. 3. Each band for the given temperature consists of four curves, showing that the currents only slightly fluctuate, irrespective of the type of substrate and the protecting coverage. Qualitatively same results were obtained for the tapes A1-A4 and B1-B4. The I_c values at self-field and 9 T are summarized in Table 1, together with the data of other tapes. The data indicate that, irrespective of the technology, substrate type, actual buffer layers, the superconducting compound, and the protection coverage, all tapes exhibited excellent results, above 50 A at self-field and 77 K. Nevertheless, some of the tapes excelled, in particular SuNAM C-type tapes at temperatures above 50 K and low magnetic fields. On the other hand, the Zr-doped tapes of SuperPower were superior at temperatures at and below 50 K, both at low and high magnetic fields. These data are in the Table 1 emphasized by shadow.

In some tapes transport current was measured with magnetic field along tape plane and perpendicular to it. It

Table 1. Engineering currents of 21 studied tapes and the lift factors I_c/I_c(77K, 0T) (after slash). At 77 K none of the tapes exhibited nonzero Ic value at 9 Tesla, therefore for this temperature B_{irr} value is given at which I_c turned to zero.

Sample	I_c (A) 77 K, 0 T	B_{irr} (T)	I_c (A) 50 K, 0 T	I_c (A) 50 K, 9 T	I_c (A) 10 K, 0 T	I_c (A) 10 K, 9 T
SuperPower						
SCS4050 7,5%Zr	124	8	556/4.48	38/0.31	1690/13.63	252/2.03
SCS4050 15%Zr	118	8	511/4.33	35/0.22	1555/13.18	230/1.95
SCS4050AP	77	8	393/5.1	27/0.35	1302/16.91	136/1.77
SCS12050 AP	84	8	390/4.64	23/0.27	1225/14.58	130/1.55
SCS 3050 AP	91	8	417/4.58	26/0.29	1405/15.44	137/1.51
SCS 4050/1	58	8	249/4.29	21/0.36	902/15.55	138/2.38
SCS 4050/2	55	7	244/4.44	18/0.33	865/15.73	130/2.36
SuNAM						
A1	142	7.7	419/2.95	13/0.092	1040/7.32	90/0.634
A2	128	7.3	369/2.88	10/0.078	831/6.49	73/0.57
A3	146	7.3	438/3.00	14/0.096	1040/7.12	89/0.61
A4	83	7.3	280/3.37	7/0.084	808/9.73	75/0.904
B1	162	7.4	439/2.71	15/0.093	987/6.09	96/0.59
B2	137	7.2	443/3.24	13/0.095	1150/8.42	91/0.67
B3, B4	135	7.5	442/3.27	12/0.089	1100/8.15	93/0.69
C1	224	8.8	631/2.82	19/0.085	1430/6.38	127/0.567
C2	218	8.5	605/2.78	16/0.073	1355/6.21	117/0.537

C3	209	8.5	578/2.77	18/0.086	1410/6.75	121/0.579
C4	171	8.5	480/2.81	15/0.088	1135/6.64	100/0.585
D1	156	7.5	468/3.00	14/0.09	1062/6.81	95/0.61
SuperOx	120	7.3	397/3.31	23/0.19	1100/9.17	150/1.25



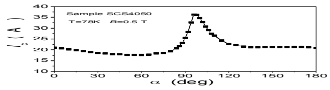


Fig. 4. The angular dependence of the transport current in the SuperPower tape SCS 4050 AP (advanced pinning, left) and of the SuperPower tape with a normal pinning, SCS 4050 (right). Both dependences were measured at 78 K and magnetic field 0.5 Tesla.

was rather surprise that the transport current with magnetic field along the plane was in one tape higher than with magnetic field along the normal, while in another tape of the same producer this relation was opposite. To better understand this fact, the transport current was measured as a function of the field angle. The results in figure 4 shows that the angular dependences of both tapes significantly differ. Both exhibit a peak close to the tape normal but the height of the peak with respect to the I_c value for α=0° (magnetic field aligned with the sample plane) strongly differs, once being lower, once higher. In Fig. 4 right the peak value is much higher than I_c(α=0°) but the peak is shifted off the α=90° position. In fact, the values for α=0° and α=90° are close to each other. So, by measuring only data

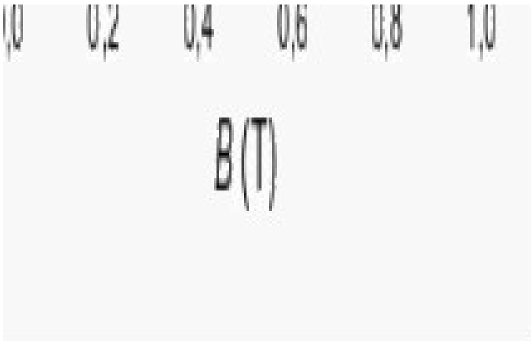
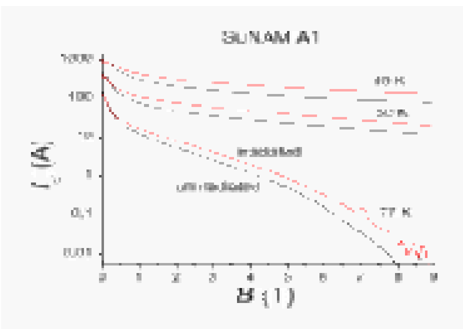


Fig. 5 Magnetic field dependence of the transport current measured in the two principal orientations α=0° and α=90° on the SuperPower tape SCS4050 doped by 15 wt.%Zr at 77 K.

Fig. 6. The angular dependence of the transport current of the SuNAM tape B_1. It is a typical dependence for all SuNAM tapes investigated in this study.



in the two principal magnetic field orientations, we can come to a wrong conclusion on the character of current anisotropy (Fig.5).

All the SuNAM tapes exhibited quite different angular dependence of I_c, where the dominant peak was exactly at α=90° and the values out of the peak were nearly constant (see Fig. 6.)

Finally, a representative set of the tapes was irradiated by neutrons to the fluence of 2.1 E22 m^{-2}. The typical effect of irradiation on I_c, observed inductively on all the irradiated tapes, is shown in Fig. 7. In all cases the self-field value was slightly lower than before irradiation, however, above some 0.5 T the I_c value after irradiation increased. Fig. 7. shows that this effect is nearly exponential with temperature.

Fig. 7. The effect of irradiation on the engineering currents observed on irradiated tapes, here represented by the results of the SuNAM tape A_1.

4. Summary

Electric current of a set of 21 superconducting tapes was measured both inductively, by means of VSM, and by current transport. The results obtained by both these methods were not identical but fairly similar, reflecting different measurements conditions of both methods. At temperatures above 50 K the copper-plated SuNAM tapes (C-type), irrespective of the substrate, exhibited maximum engineering currents, especially at low magnetic fields. At and below 50 K the maximum I_c was found in SuperPower tapes doped by Zr, up to 9 T.

The transport experiments allowed for measurements with arbitrarily oriented magnetic field. The angular dependence of I_c was somewhat more complicated in all SuperPower tapes than in SuNAM tapes. This, however, might be positive in practical applications.

Irradiation by the neutron fluence of 2.1E22 m^{-2} resulted in a slight I_c decrease in self-field but a significant increase at magnetic fields above 0.5 T. This increase was nearly exponential with temperature. Qualitatively same effect of irradiation was observed in all investigated samples, irrespective of the preparation method, composition of the superconductor compound, and the other components. A more comprehensive report on the neutron irradiation effects is under way.

Acknowledgments

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