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Superior properties of SmBCO coated conductors at high magnetic fields and elevated temperatures

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ABSTRACT

In addition to the well investigated $YBa_2Cu_3O_{7-\delta}$ (Y-123, YBCO) compound, many other rare earth-123 compounds are candidate materials for the production of coated conductors. Sm-123 seems to be an excellent alternative because of its higher transition temperature (T_c) and higher critical current densities (J_c) in external magnetic fields. Because of the fast decrease of J_c in YBCO at elevated temperatures, especially around the boiling point of liquid nitrogen, the slightly higher T_c can be an important advantage. Recently, significant progress has been made in the production of long length Sm-123 based coated conductors. We report here on transport measurements on these conductors in the liquid nitrogen temperature range. The critical current densities were determined as a function of the applied field and the crystallographic orientation under maximum Lorentz force configuration. A shift of the *c*-axis ($\sim$7°) from the tape normal was found. The conductor properties were compared to those of commercially available YBCO coated conductors. The critical current densities as well as the irreversibility fields are higher in the SmBCO tapes, thus demonstrating the superior properties of the Sm-123 compound.

1. Introduction

The properties and the production process of coated conductors, especially of $YBa_2Cu_3O_{7-\delta}$ (YBCO, Y-123) tapes, improved dramatically during the past few years. Various vapour deposition and metal organic deposition methods [1–5] were introduced as well as different novel substrate and buffer layers. Nowadays, long lengths of YBCO tapes are commercially available with good superconducting properties, but their potential for applications in high magnetic fields at elevated temperatures ($\sim$77 K) is restricted [6]. Other REBCO (rare earth, RE-123) compounds promise a smaller field dependence of the critical current density at high temperatures because of their higher irreversibility fields [7,8]. It seems favourable to use them instead of YBCO for the fabrication of HTS coated conductors in order to improve the in-field critical current density (J_c) [9]. In particular, substitution of yttrium by samarium (Sm-123) results in a higher superconducting transition temperature (T_c) and higher J_c at high magnetic fields [11].

The potential application of coated conductors strongly depends on the production speed, costs, available lengths, mechanical strength, and the superconducting properties. The production process, the substrate as well as the buffer architecture must be optimized to reach this target. A problem is the necessary higher growth temperature during the fabrication process. The influence of this production parameter on the superconducting properties was studied elsewhere [10]. The production process is currently still very time consuming and the properties of small test samples often cannot be achieved in long length technical conductors. It was demonstrated recently, that long length SmBCO coated conductors can be produced with a similar speed as YBCO coated conductors [11]. The superconducting properties of these tapes at high magnetic fields and elevated temperatures were investigated in the present study and compared to the best commercial YBCO conductors we have investigated in the past [6].

2. Experimental

The coated conductor was produced by a thermal co-evaporation technique (evaporation in a drum in a dual chamber). This technique allows a uniform deposition of the SmBCO layer [12]. The substrate consists of a polycrystalline metal tape (Hastelloy C-276) which was electro-polished and ion-milled to a RMS roughness of about 2 nm, followed by barrier and nucleation layers of Al_2O_3, Y_2O_3, IBAD-MgO, homo epi-MgO, and $LaMnO_3$. An approximately 5 μm thick silver layer was coated on top of the SmBCO layer. The thickness of the SmBCO layer was 2.2 μm and the tape has a width of 4 mm. The end-to-end critical current was found to be 122 A at 77 K and self field [11].

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Four probe measurements were made to determine the transport properties of short samples which were cut from a long conductor. The field and the angular dependence of J_c were assessed in a 6 T split coil magnet system. All data refer to the maximum Lorentz force configuration ($H \perp J$). High field measurements up to 15 T were performed in another cryostat. The measurements were done under helium gas flow in the temperature range between 70 and 85 K. The length of the samples was limited to 27 mm by the available sample space in the cryostat. Pressed current contacts were used due to their lower resistivity, their good reproducibility and easy removability. 1 μV/cm criterion was used to define the critical current.

The superconducting transition temperature and the irreversibility line were measured resistively by applying a small current (3 mA) and reducing the temperature slowly until the voltage dropped to zero. Different criteria were used to define the critical temperature (see below). An electric field criterion of 1 μV/cm was chosen for the irreversibility temperatures. The homogeneity of the samples was determined by magnetoscan measurements [13]. This non-destructive technique allows identifying macroscopic defects in coated conductors.

3. Results and discussion

The samples are highly homogeneous as demonstrated by magnetoscan measurements. The measured magnetic field profile of one sample is presented in Fig. 1a. No larger defects or areas with low critical currents were found in any sample. The sample to sample variation in the field profile was negligible which ensures comparable critical current densities in all samples [13]. The peak-field of the shielding currents was 16 mT at an applied field of 52 mT. This is somewhat higher than for comparable YBCO conductors [13] at similar conditions and promises higher critical currents in the SmBCO conductors.

The critical temperature defined by a two tangent criterion was found to be $T_c^{tan} = 94.45$ K. In addition, the onset ($T_c^{onset} = 94.56$ K) and the zero resistance temperature ($T_c^{zero} = 94.15$ K) were evaluated (Fig. 1b). T_c is higher by about 3–5 K than in commercial YBCO coated conductors [6]. The transition width (ΔT), calculated from the difference between onset and zero resistance temperature, was 0.41 K, being only 0.4% of T_c, which indicates again a high homogeneity of the superconducting properties.

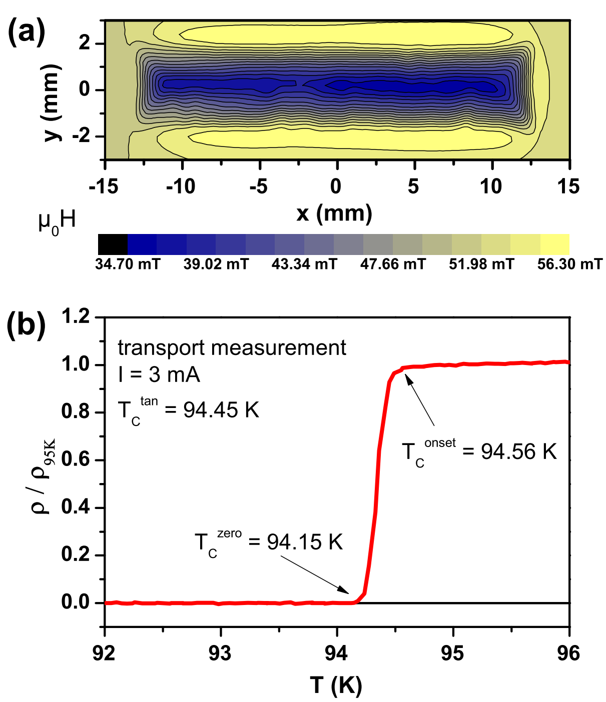

Fig. 1. (a) The high homogeneity of critical currents is evidenced by magnetoscanning. (b) Sharp resistive transition at self field.

The crystallographic orientation of the superconducting layer is inclined with respect to the tape geometry. This can be seen from angular resolved J_c measurements (Fig. 2). A Hall probe was mounted parallel to the tape surface, in order to monitor the real orientation of the superconductor within the field. The large peak was found to be shifted by ~7° with respect to the sample surface. The second (small) peak correlates with the growth direction (perpendicular to the tape); thus, correlated defects grow perpendicular to the tape (not along the crystallographic c-axis). The large peak is a manifestation of intrinsic pinning by the layered crystal structure, which causes a periodic variation of the order parameter along the c-axis. The peak could, in principle, also result from correlated disorder, as demonstrated in Ref. [14]. (Y, Sm)$_2$O$_3$ nanoprecipitates were found to self-align in planes tilted by 5° with respect to the ab planes. The interplay of these planes with the crystal structure caused the peak to shift with field and temperature. The peak was shifted by up to ~12° at low fields and temperatures, but aligned with the ab-planes at high temperatures or fields, where the density of the (Y, Sm)$_2$O$_3$ precipitates is too low and the maximum in J_c is caused by intrinsic pinning. Intrinsic pinning is found to dominate at and above 2 T at 77 K [14]. Since our measurements were done in this regime, we conclude that the large peak is the intrinsic ab-peak. The misalignment between the crystallographic orientation and the tape geometry results from the actual production process and is of course not a property of the Sm-123 phase.

The irreversibility lines were measured with the field parallel and perpendicular to the sample surface and for $H \| ab$ (Fig. 3). The irreversibility fields (H_{irr}) are higher than in the YBCO reference samples in the whole temperature range investigated [6]. The irreversibility temperature (T_{irr}) was found to be 85 K ($H \perp$sample surface) and 73 K ($H \|$sample surface) at the highest applied field of 15 T. H_{irr} is 12 T at 77 K in the SmBCO coated conductor ($H \perp$sample surface), being higher by 3 T than in the best YBCO reference conductor. This clearly demonstrates that the Sm-123 compound can be operated at higher fields than Y-123, which confirms earlier reports [7,8,10]. The difference in H_{irr} between the field orientation parallel to the tape surface and to the ab-planes is not as

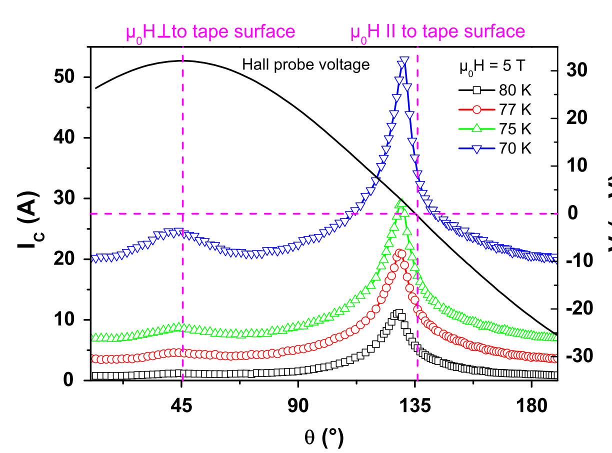

Fig. 2. Angular dependence of the critical current at 5 T and several temperatures. The solid black line presents the Hall voltage, which is proportional to the magnetic field component perpendicular to the tape surface. The small peak is caused by correlated disorder, the large by intrinsic pinning.

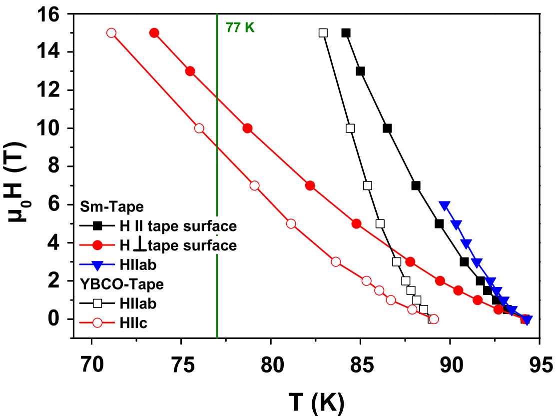

Fig. 3. Irreversibility line for the field applied parallel and perpendicular to the tape surface as well as for the field oriented parallel to the *ab*-planes (solid symbols). The open symbols refer to commercial YBCO coated conductors with high irreversibility fields.

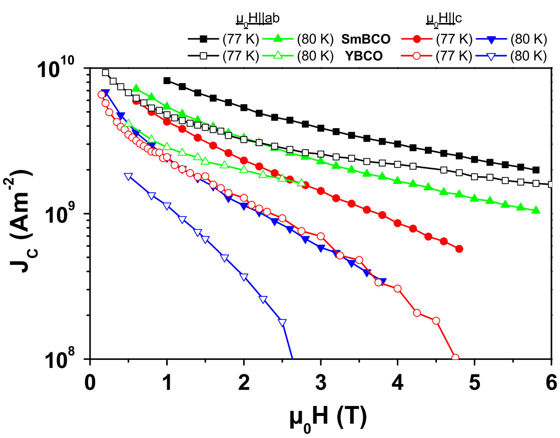

Fig. 4. Field dependence of the critical current density at 80 K and 77 K. The solid symbols refer to the SmBCO coated conductor, whereas the open symbols refer to a commercial YBCO reference tape.

pronounced as might be expected from the sharp peak in the angular resolved measurements of J_c.

High critical currents at high magnetic fields are required for many applications. A lot of effort was made to enhance the in-field behaviour of different materials. Furthermore, the use of a low-cost cooling medium (liquid nitrogen) is favourable, which restricts the operation temperature to 77 K at ambient pressure. Up to now, only RE-123 coated conductors demonstrate a high performance under these operating conditions. The present SmBCO coated conductor shows significantly higher critical current densities than industrial Y-123 coated conductors [6] at 77 K and above (Fig. 4). J_c is higher in both main field orientations. Whereas the critical current in YBCO conductors decreases rapidly with increasing fields, when applied parallel to the *c*-axis at high temperatures, J_c remains high in SmBCO conductors. The SmBCO tapes are more stable against small temperature variations due to the smaller decrease of J_c with increasing temperature.

4. Summary

We demonstrate that SmBCO coated conductors produced in an industrial process have superior properties than comparable YBCO conductors, in particular at high fields and elevated temperatures. It can be expected that using Sm-123 instead of Y-123 would increase the maximum operating field in liquid nitrogen by 2 or 3 T, which is important in view of potential applications for coated conductors.

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