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High critical currents in Ag-BSCCO(2223) tapes: Are the grain boundaries really 'weak-links'?

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Abstract

The remarkable improvement of the superconducting properties of polycrystalline BSCCO(2223) when processed into Ag-clad tapes has been investigated with magnetisation measurements. The tape bulk critical current density has been compared directly with the *intragrain* critical current of the crystalline powder extracted from the tapes.

The results show that two factors contribute to the excellent tape performance: Intragranular flux pinning is much stronger than might be expected from single crystal data, and the grain boundaries display no evidence of being 'weak-links'.

1. Introduction

The disappointing critical current performance of ordinary polycrystalline HTS materials is well known to be associated with the weak-link (WL) nature of most grain boundaries (GB) [1, 2]. Although single crystals can often support high critical currents (J_c's), the GB's in bulk materials have much lower critical currents and furthermore are extremely sensitive to applied magnetic fields.

The surprisingly good behaviour of pressed Ag-sheathed BSCCO(2223) tapes [3, 4] is extremely promising for applications, but indicates also that for some reason the GB's have unusual properties [5], or are being circumvented. The mechanism underlying this improvement is therefore of great interest.

One hypothesis, the "Brickwall" model [6], is that in a highly textured plate-like polycrystalline material, as within a pressed tape, the small area grain boundaries that interrupt the flow of current in the *a-b* plane are short-circuited by *c*-direction current flow across the large-area grain boundaries between adjacent crystallite layers. However, it is well-known that in the more two-dimensional (2D) compounds, such as the (2212) and (2223) Bi phases, the coupling between Cu-O planes is weak, and the c-axis critical current is small. Also, although there is substantial texturing in these tapes, it is far from perfect. Hence, it is difficult to see how this model can account for the tapes' ability to sustain large critical currents to high temperatures. Furthermore, there are strong indications that at high temperatures, the limiting factor is weak pinning *within the grains* [7], and not the GB's.

The key issue to be addressed in understanding these tapes is therefore the relative importance of *inter*granular and *intra*granular critical currents. Transport measurements examine the former alone, while the sample magnetisation has contributions from both. However, if weak-links are present, they contribute a well-defined "necking down" feature [8] to the magnetisation that is a characteristic signature of sample granularity. Also, we have developed recently a quantitative analysis of magnetisation data, the length scale technique [9], that allows the *inter*granular contribution to be isolated. Here we apply this approach to the Ag-sheathed BSCCO(2223) tapes.

2. Experimental

Ag-sheathed BSCCO(2223) tapes were made by the powder-in-tube method, as described in Ref 10, with subsequent pressing and annealing to a final cross-section of 3 mm width and 0.1 mm thickness, roughly half this thickness being superconductor. The grains are in the form of platelets, of typical size 10 µm by 1 µm.

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Scanning electron micrographs show a certain degree of texturing, with most grains aligned with the *c*-axis perpendicular to the plane of the tape.

Three samples - 91402-2, 91402-3 and 911129-8, each 10mm long, were looked at; most of the data reported here were taken on Sample 91402-2. The magnetisation measurements were made with a vibrating sample magnetometer (Oxford Instruments VSM 3001) at temperatures between 10 K and 90 K, and at fields up to 8 T. Some flux creep was evident, but it was small enough to be unimportant for the present analysis.

In order to assess the behaviour of the BSCCO(2223) grains in comparison with the tape, sample 91402-2 was cut open and the powder scraped out and put into wax; we estimate that 95% of the powder was conserved.

A further comparison was made with a BSCCO(2212) single crystal, which had been grown by a directional solidification method employing a stationary crucible in a strong temperature gradient (10 C/cm); it had dimensions 3 x 4 x 0.1 mm^3.

The data are best considered in terms of the sample magnetic moment m, which is the quantity measured by the VSM, rather than the magnetisation M. For a tape sample with the field perpendicular to its face (i.e., parallel to the average *c*-direction of the textured grains), the irreversible moment Δm can be written

$$\Delta m = \Delta m(\text{intra}) + \Delta m(\text{inter}) \qquad (1)$$

where the two terms represent intra- and intergranular contributions respectively. In terms of $J_c(gr)$, the intragranular critical current, and $J_c(gb)$, the intergranular critical current which corresponds to the transport critical current, we can write

$$\Delta m = (2\Omega/3)\,[f\, a\, J_c(gr) + \Lambda\, J_c(gb)] \qquad (2)$$

where Ω is the sample volume, a is a typical grain size, and Λ is the length scale on which the intergranular currents circulate [9]. In a well-connected superconductor, Λ should be equal to the sample size. f is the filling factor of the superconducting grains within the interior volume of the sheath, and for present purposes can be put equal to unity.

It is important to appreciate from equation (2) that the large ratio of Λ to a, typically 10^2 in our tapes, weights strongly the intergranular contribution to the measured Δm of a tape sample even if $J_c(gb)$ is considerably less than $J_c(gr)$; on the other hand, in a powder sample the second term is absent.

Λ can be derived directly from the 'reverse-leg' slope dm/dH of a magnetisation loop, provided that the second term of equation (2) is dominant [9]. However, if the first term contributes significantly to the moment, then dm/dH yields an underestimate of Λ. Useful measurements of Λ require that the applied field is large compared with the penetration field H^*.

3. Results and Discussion

The measured length scale Λ of the tape sample 91402-2 at 77 K (Figure 1) is consistent with the sample dimensions, and so demonstrates directly that the dominant contribution to the sample magnetic moment derives from large-scale intergranular currents. Λ decreases only slightly from 3.2 mm at 5 mT to 2.8 mm at 40 mT; at this temperature the irreversibility field H_{irr} is of the order of 100 mT. This situation is very different from that in polycrystalline YBCO, where just a few mT is enough to decouple the grains and so cause a drastic reduction in length scale.

At 10 K (Figure 2), Λ is slightly smaller, decreasing from 2.2 mm at 1 T to 0.9 mm at 8 Tesla. It is therefore

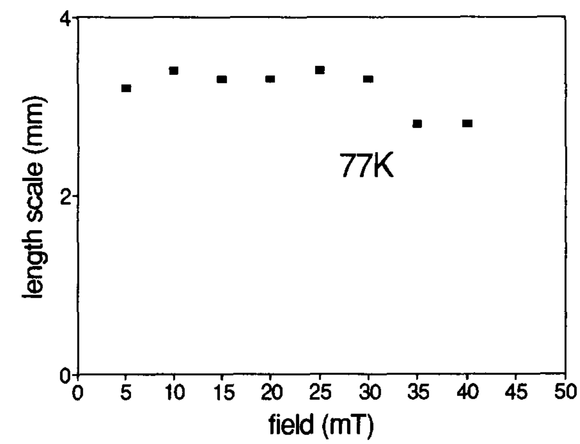

Figure 1. Variation of the length scale Λ with field at 77 K for tape sample 91402-2.

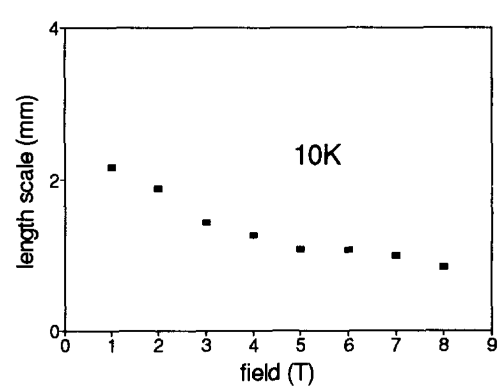

Figure 2. Variation of the length scale Λ with field at 10 K for tape Sample 91402-2.

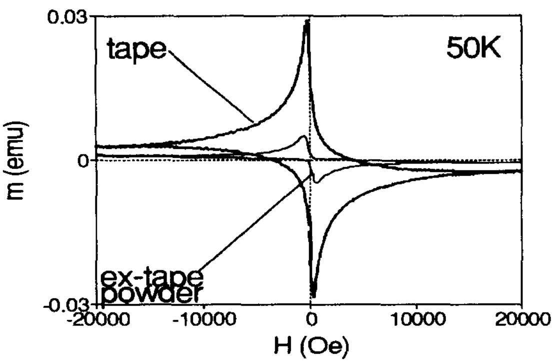

Figure 3. m-H loops at 50 K for tape sample 91402-2 and for the powder extracted from this sample.

somewhat smaller than the sample dimensions (although far larger than the scale of the grains), which suggests that at this temperature, the grains are making a significant contribution to the magnetic moment, and so reducing the measured dm/dH on the 'reverse leg'.

A comparison of the measured magnetic moments of the tape and the ex-tape powder is shown in Figure 3. At all fields and temperatures, the former is nearly an order of magnitude larger than the latter, which shows directly that in equation (2) by far the dominant contribution to the tape Δm is from the second, *intergranular*, term (the contributions of $\Delta m(gr)$ are not quite identical in the two samples, because the tape is substantially textured, whereas the powder has random orientation; however, the difference is negligible in the present context).

We can now obtain $J_c(gb)$ from the tape Δm and measured Λ's, and also an estimate of $J_c(gr)$ from the powder Δm and an assumed typical grain dimension of 10 µm; the J_c's derived from the zero field remanent moments are shown in figure 4. It would be interesting to compare these data with measurements on a single crystal, but to our knowledge no single phase (2223) crystals have ever been grown (reflecting the complexity of the BSCCO phase diagram and the extremely limited stability of the (2223) phase). Instead, we use a (2212) phase crystal for the comparison, with the temperatures normalised to the respective transition temperatures of 87 K and 105 K. It is evident that the (2223) ex-tape grains have far higher critical currents than the (2212) single crystal, and that the enhancement increases with increasing temperature. Recent reports [11] suggest that defects introduced during the tape processing may be responsible for the additional pinning.

On the other hand, the ratio of $J_c(gr)$ to $J_c(gb)$ hardly changes over the entire temperature range (Figure 5), and is only one order of magnitude, in contrast to the many orders of magnitude and the field and the temperature sensitivity that are found in polycrystalline YBCO. The size and relative constancy of this ratio, both with respect to temperature as shown in figure 5, and with respect to field as shown in figure 3, argue strongly against the presence of significant weak-links within the (2223) tapes.

The fact that $J_c(gb)$ is an order of magnitude less than $J_c(gr)$ could be accounted for merely by the limited connectivity of the grains within the tapes, as the micrographs show that the texturing and packing of the present sample is far from perfect. It is noteworthy that the highest reported tape critical currents [12] are about an order of magnitude larger than that of the samples described here and so are of about the same size as our $J_c(gr)$.

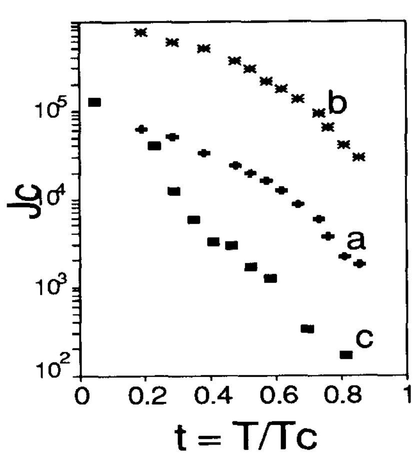

Figure 4. Critical current densities (zero field) of (a) (2223) tape; (b) the powder extracted from that tape; (c) a (2212) single crystal.

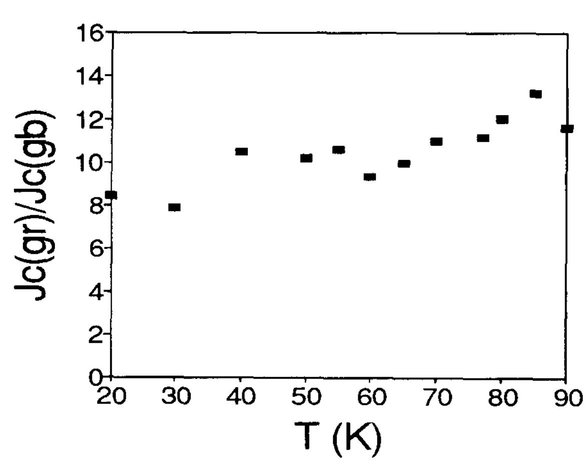

Figure 5. Tape sample 91402-2; ratio of the (zero field) $J_c(gr)$ to $J_c(gb)$ as a function of temperature.

5. Conclusions

Our magnetisation measurements show that the Ag/BSCCO(2223) tapes are fully connected at high temperatures and in fields up to the irreversibility line. Thus, in sharp contrast to the behaviour of polycrystalline YBCO, there is *no* indication of the fragmentation of the pattern of current flow associated with grain boundary 'weak-link' behaviour.

Comparison of J_c(gr) for the ex-tape powder with a BSCCO(2212) single crystal shows that the tape-processed grains have far stronger pinning, particularly at high temperatures. We suggest that the tape processing is crucial in providing the additional pinning.

It seems therefore that the tape processing, which has to be extremely tightly controlled to obtain the best performance, not only increases the pinning within the grains, but also allows the grains to grow in a manner that enables supercurrent to flow easily across the grain boundaries. To understand how these improvements come about is an exciting but formidable task; however, when understanding is achieved, it should allow further substantial increase in performance.

Acknowledgments

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