

Fast Healing of Deformation-Induced Damage in Ag/Bi-2223 Tapes

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Abstract— Critical current, magneto-optical (MO) images and ac susceptibility of Ag/BSCCO-2223 tapes were studied at various stages of tape processing. It was found that long-range connectivity of the tape core destroyed by intermediate deformation was restored in less than 1h of subsequent sintering. Transverse flux penetration observed in MO images of sintered tapes are supposedly weak link channels remaining at locations of unhealed or only partially healed deformation-induced cracks.

Index Terms— ac susceptibility, BSCCO, cracks, magneto-optical image, superconducting tapes

I. INTRODUCTION

Ag/Bi-2223 tapes show great potential for various high-current applications such as power transmission cables, transformers, motors etc [1]. Recent findings of unhealed cracks in fully processed high- J_c multi-filamentary tapes [2,3] revealed one of the important factors limiting the current-carrying ability of such tapes. Therefore healing the cracks created in the tape core by intermediate deformation, is a crucial problem to be addressed in order to further enhance their current-carrying ability, which is still below their true potential, which is probably well above 10^5 A/cm^2 [4], [6], [6]. Our recent ac susceptibility data have shown rapid crack healing in monofilamentary tapes in the early stage of post-deformation sintering [7-9]. Here the results of more detailed studies, including transport and magneto-optical data are presented.

II. EXPERIMENTAL DETAILS

Ag/Bi-2223 single-filamentary tapes were fabricated by the oxide powder-in-tube method. The details of the tape fabrication process have been published elsewhere [7-9]. Silver tubes of 6 mm in diameter and of wall thickness 1mm were packed, closed, drawn and flat rolled. Tape sintering was performed in air. Sintering temperature, T_{sin} , was in the range of 830 to 840° C. Rolling was used for the intermediate

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deformation between the two sintering steps. Final tapes have 2.5-3.5 mm width and 0.1-0.2 mm thickness. The effective duration of the second sintering, t , was varied from 0.5 to 60h. In order to compare long and short term sintering, t was taken as the time spent between 800°C and T_{sin} .

Critical current density, J_c , was measured by the DC, four-point probe method at 77 K using a $1 \mu\text{V/cm}$ criterion. AC susceptibility, $\chi(T)$, was measured at 747 Hz from 77-120 K. An AC field of $\sim 0.005 \text{ mT}$ was applied normal to the tape broad face.

MO characterization was carried out with the silver sheath removed from the broad face of tape by chemical etching [2]. The garnet indicator film was placed on the broad tape face. The MO pattern displays the normal component of the field above the sample surface [2,3,9].

III. RESULTS AND DISCUSSIONS

Figure 1 illustrates the J_c evolution from the end of the first sinter through the second sinter. The drastic J_c reduction (tape b) caused by intermediate rolling (IR), and the initially rapid, then more gradual growth of J_c as the second sintering (tapes c-g), proceeds are quite clear.

The evolution of magneto-optical (MO) images of the tapes processed under the conditions of Fig. 1, is shown in Fig. 2. The as-rolled tape b demonstrated no meaningful contrast due to the suppression of screening currents by the rolling damage, therefore its MO image is not presented. Post-deformation sintering resulted in significant improvement of the core connectivity, as shown in Fig. 2. The

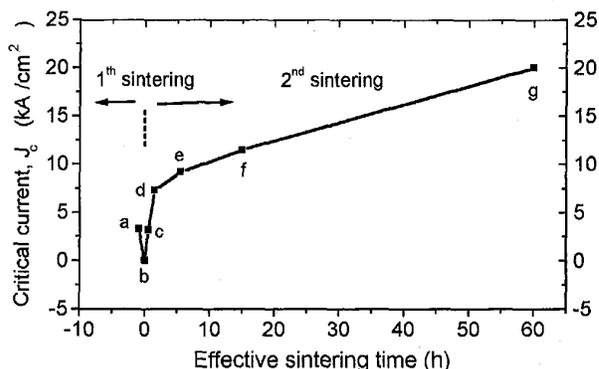


Fig. 1. Time evolution of critical current density during thermo-mechanical processing of Ag/Bi-2223 tapes: (a) after the 1st sintering; (b) as-rolled after the 1st sintering; (c) post-IR after further heating/cooling during 0.5h ramp; (d-g) after the 2nd sintering of 1.5h to 60h.

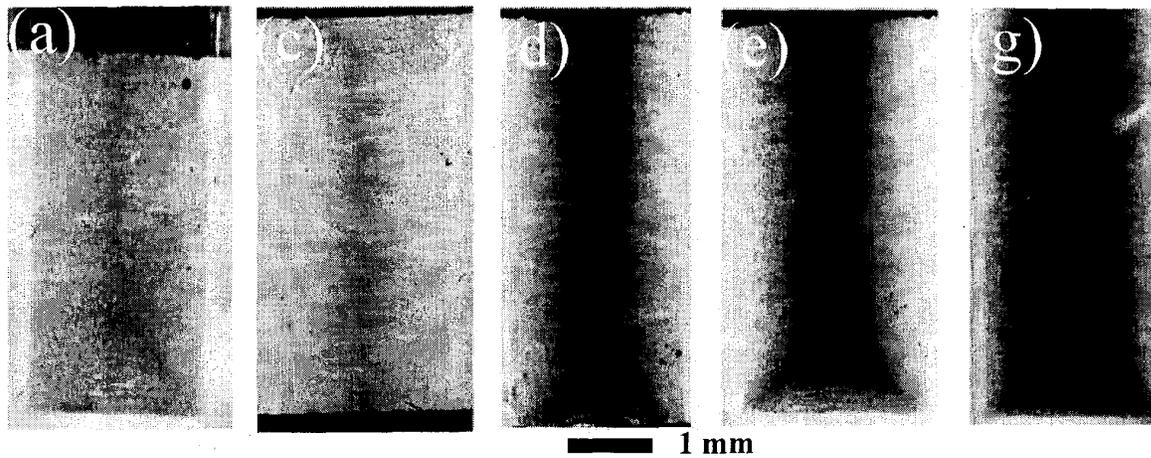


Fig.2. MO images of taken at $T=13\text{K}$ and $H=20\text{mT}$ after zero field cooling (ZFC). Tapes were processed as in Fig. 1: (a) after the 1st sintering; (c) post-IR after further heating/cooling during 0.5h ramp; (d)-(e)- (f)-(g) – after the 2nd sintering of 1.5h to 60h . The dark areas on the images correspond to well-screened areas, while lighter areas are more strongly -penetrated by the external field. The growth of shielding with increasing sintering time is clear.

darker, well-screened areas grow progressively. After the first sintering process, Fig. 2(a), there are no significant bulk current flowing in the sample. The initial process of damage healing during the second sintering proceeds so rapidly that long-range connectivity, as evidenced by the dark mid rib separating oppositely flowing currents, is observed even after only a 0.5 h long heating/cooling cycle (Figs. 1, 2, tape c). MO images for tapes d-e-g in Fig. 2 demonstrate progressive growth of this long-range connectivity with increased sintering, further progress already being evident at 1.5h (tape d). The screening current increases significantly from tape c to g, as is clearly demonstrated by the increase in the width of the dark shielded central core. These data correlate well with the transport current density data in Fig.1.

Increasing the external field from 20 to 60 or 80 mT causes

deeper flux penetration and the development of a clearer roof pattern in the induced currents (Figs. 3 and 4). As seen in Fig. 4, the apex angle of the triangles formed by the “Discontinuity (D) Lines” where the screening current turns, is not 90° , but $\sim 100^\circ$. This means that less cross-section is needed to support the transverse current than is needed for the longitudinal current and that the transverse current density is thus higher. Figure 4 also shows that there are many easy flux penetration channels (EFPC), which remain whatever the sintering time. They become progressively more visible as the field increases, as can be seen by comparing Figs. 2 through 4, where the applied field rises from 20 to 80mT.

The evolution of the ac susceptibility during tape processing is manifested in Figs. 5 and 6. $\chi(T)$ measurements probe on scales: from that of the sample size (tapes a and c-g)

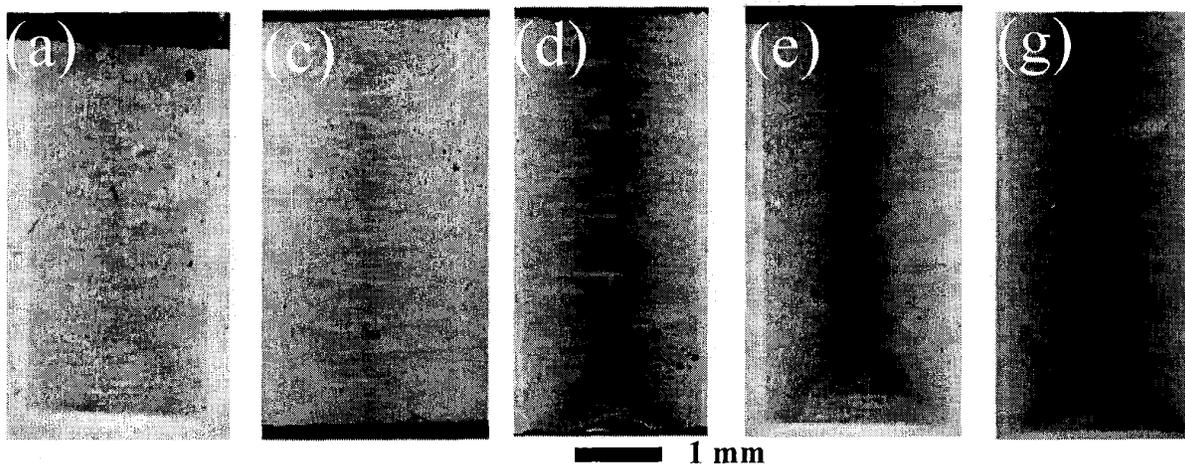


Fig. 3. MO images of Ag/BiSCCO-2223 tapes taken at $T=13\text{K}$ and $H=40\text{mT}$ (ZFC) All tapes subjected to different processing. Symbols on the pictures relate to the same states as those in Fig. 1: (a) after the 1st sintering; (c) post-IR after further heating/cooling during 0.5h ramp; (d)-(e)- (f)-(g) – after the 2nd sintering of 1.5, 5..5, 15..5 and 60h . The dark areas on MO pictures correspond to well-screened parts, light areas correspond to the

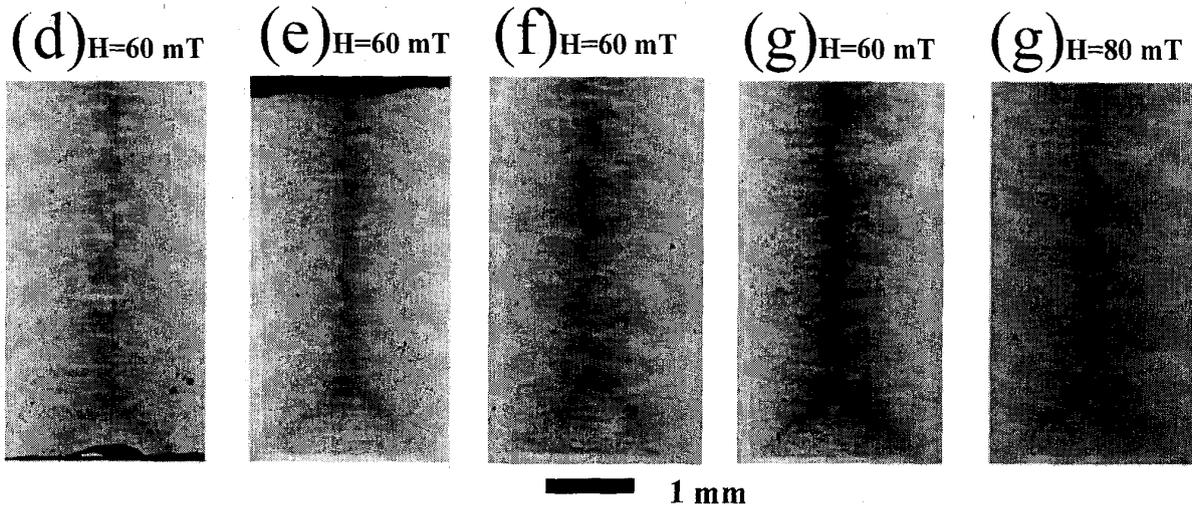


Fig. 4. MO images of Ag/BiSCCO-2223 tapes "d-e-f-g" taken at ZFC at $T=13$ K and $H=60$ mT. Tape g was also imaged in higher magnetic field of 80 mT. Symbols on the pictures relate to the same states as those in Fig. 1. Tapes d, e, f, g had 2nd sintering times of 1.5, 5.5, 15.5 and 60h. The dark areas correspond to well-screened regions.

to the significantly smaller sizes (tape b), where circulating currents are more confined. Fig. 5 displays a dramatic broadening in the χ'' peak by about 6 times of the superconducting transition (SCT) at T_c [7] for tape b after IR. This broadening results from the reduction of large-scale current loops. Accordingly, the $\chi(T)$ behavior after IR is dominated by small-scale current loops with a wide spectrum of size and link strengths. Rapid recovery of a sharp SCT in the $\chi(T)$ traces for 0.5h-sintering (Fig. 5d) is indicative of the rapid restoration of long-range core connectivity. The values of full width at half maximum (FWHM) of the χ'' peaks, δT , characterizing the SCT broadening, are presented in Figs. 5 and 6.

Rapid damage healing at the beginning of the second sintering was followed by significantly slower changes at longer times. The J_c growth rate slows markedly for sintering time $t \geq 1.5$ h (Fig. 1, tapes e-g). The narrowing of the SC-transition in the $\chi(T)$ traces in Fig. 5 and 6 demonstrates the same trend: δT is reduced strongly from 2.8K for tape c (heating/cooling treatment) to 0.8K for tape d (1.5h-sintering) (Fig. 5). The corresponding δT for 1.5h (tape d) and 60h

(tape g) sintering are very close, 0.8 and 0.7K, respectively (Fig. 6). The same slow process is responsible for the gradual disappearance of easy flux-penetration channels (light transverse strips in MO images of tapes c-g) in the tape core (Fig. 2-4).

On the basis of the results presented above, it appears that a considerable fraction of the IR-induced cracks are quickly healed in the first hours of the sintering. But either the liquid phase that enables this healing is then exhausted or the residual cracks are too wide to bridge and the rate of healing decreases. The residual transverse flux-penetration channels observed in the MO images (Fig. 2-4) appear to be weak-links. As noted by the angle of the D lines not being 90° and the transverse J_c being higher, they clearly produce a small anisotropic effect on the current flow. The smallest effective resolution in the present MO examination on such samples is of order 0.1 mm. But there is evidence from transmission electron microscopy [10] that the healing of cracks is not complete in single grains. In fact it is sometimes possible to view grains that exhibit quasi-periodic open steps that appear to be the trace of a former crack. Clearly however these steps

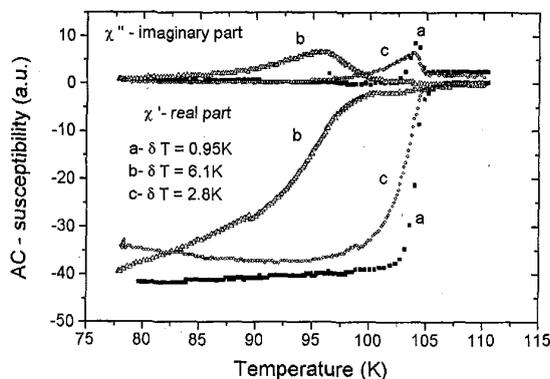


Fig. 5. AC susceptibility vs. t traces of Ag/BSCCO-2223 tapes to different processing. Symbols at the curves related states as those in Fig. 1; δT -FWHM of χ'' peaks.

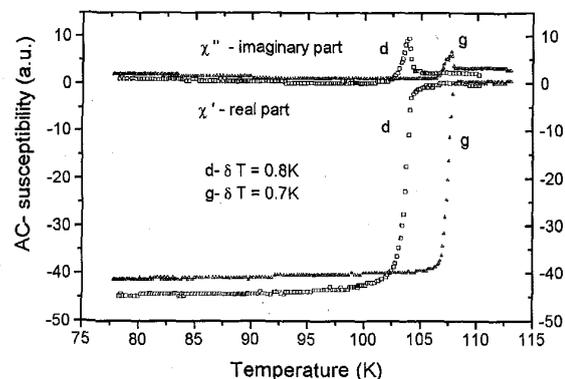


Fig. 6. AC susceptibility vs. t traces of Ag/BSCCO-2223 tapes subjected to the 2nd sintering for various periods. Symbol at the to the related to the same states as those in Fig. 1.

do not pass current and may contribute to the general transverse flux penetration. On the other hand, the fact that the current is *almost* isotropic means that major damage is healed. If current percolates strongly on scales smaller than 0.1 mm, this is apparently for other reasons than the damage introduced at the IR step.

IV. SUMMARY

Damage (crack generation in particular) induced in Ag/Bi-2223 tape cores by intermediate rolling (IR) is effectively healed in the first hours of the second sintering. Long-range core connectivity destroyed by IR is established already during heating to the sintering heat treatment, as revealed by transport, MO and magnetic observations.

The two-step character of connectivity evolution during the tape second sintering implies the possibility of two subsequent different healing processes: crack healing (I) and the improvement in fine-scale core connectivity (II).

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