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Analysis of transport critical current density in a bent Bi–Pb–Sr–Ca–Cu–O silver-sheathed tape

W.D. Lee ^a, L. Horng ^b, T.J. Yang ^{c,*}, B.S. Chiou ^a^a *Institute of Electronics, National Chiao-Tung University, Hsinchu, Taiwan*^b *Materials Research Laboratories, Industrial Technology Research Institute, Chutung, Hsinchu 31015, Taiwan, and
Dept. of Physics, National Chang-Hua University of Education, Chang-Hua, Taiwan*^c *Dept. of Electro-physics, National Chiao-Tung University, Hsinchu, 30050, Taiwan*

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Abstract

The experimental results on the magnetic behavior of the transport critical current density in a bent Bi based superconducting tape have shown that the irreversible strain limit ϵ_{irrev} for the onset of permanent strain damage to Ag sheathed superconductors is not dependent on the magnetic field, nor does the normalized $I_c(H, \epsilon)/I_c(0, \epsilon)$ current depend on the strain at least up to 0.5 T at 77 K. Such a behavior has been attributed to two reasons: (1) The intrinsic pinning properties are unchanged in a bent tape; (2) The strain effect is extrinsic and arises from superconductor cracks. Thus, based on these arguments a Josephson junction tunneling model with cracks in between the grain boundaries is proposed to explain the J_c behavior quite well for a bent granular high- T_c superconducting tape. Our model calculation shows that the critical current density of high- T_c superconductor may be enhanced by increasing the strain tolerance ϵ_{irrev} and the ϵ_{irrev} is determined by the properties of Ag sheathed tape and its related material parameters, which are dependent on the connectivity of the grain boundaries.

1. Introduction

Since the discovery of the high- T_c superconductors, many research has been done in developing practical magnet applications of these materials. One of the most important issues for this purpose, i.e., the transport critical current density characteristic under a magnetic field has been extensively studied [1–4]. But, as we know, although a relatively large magnitude of the bending stress is usually encountered in the superconducting magnets construction, as de-

scribed in the A-15 superconductors by Ekin [5,6], the relationship among the transport J_c , structure of the grain boundaries, and external bending strain ϵ (bending radius R) has not been well established. However, the irreversible limit strain (strain tolerance) ϵ_{irrev} is one of the most important parameters, which are needed for the optimization of the superconducting and mechanical properties, and the ϵ_{irrev} is determined by the appearance of cracks at the Ag sheath superconductor boundary, and can be recorded reliably through acoustic emission (AE) [7].

We summarize our previous studies [8] on the magnetic field dependence of transport critical current density in a bent Bi based tape that provides

* Corresponding author.

significant physical insights into grain-boundary weak-link and transport properties. From our experimental data, it is noted that for all bending strains ε , the normalized transport critical current $I_c(H, \varepsilon)/I_c(0, \varepsilon)$ curves are superimposed on the same curve and the $\varepsilon_{\text{irrev}}$ is independent of the magnetic field within the range from zero to 500 G at 77 K. Such and similar properties also have been observed in BSCCO/Ag tapes by Ekin et al. [9].

To explain their experimental results, Ekin et al. suggested that the only effect of the J_c degradation is the irreversibility of the J_c versus ε curves about $\varepsilon_{\text{irrev}}$, which results in superconducting fracture. Fang et al. [10] also proposed a new model, which is based on the earlier “brick wall” model proposed by Bulaevskii et al. [11], to explain the behaviors of the transport critical current observed experimentally. They also suggested that this decrease in I_c is attributed to mechanical fracture and a series of transverse cracks along the length of the BSCCO/Ag tape, and a large strain (more cracks) reduces the distance between transverse cracks, and consequently decreases the critical current of the composite conductor. On the other hand, Shi [12] proposed that the magnitude of the transport I_c is proportional to the total area of the strongly coupled regions at the grain boundaries. Therefore, it is reasonable to consider that these relations between cracks and grain bound-

aries are expected to play an important role in determining the critical current of granular high- T_c superconductor.

In this paper, the goal is to develop an analytical model that can predict the effect of the transverse cracks on the critical current in a bent tape. Good agreement between numerical calculations and our experimental results is obtained, and it is suggested how to improve the Ag sheath and to enhance these materials parameters related to coherence and connectivity of grain boundaries. It is expected that one is enabled to develop a high strain tolerance and high critical current.

2. Experimental procedure

The samples used here were silver-sheathed tapes produced by the conventional powder-in-tube technique, which is a combination of fabricating techniques such as swaging, drawing, rolling and heat treatment, as described in Ref. [13]. The samples with transport critical current density J_c were about 2 to 3×10^4 A/cm² and X-ray diffraction showed that the (001) peaks of the 2223 phase ($T \cong 107$ K) were preferentially reflected. This indicates that the ab planes of the superconducting grains were parallel to the surface of the tape.

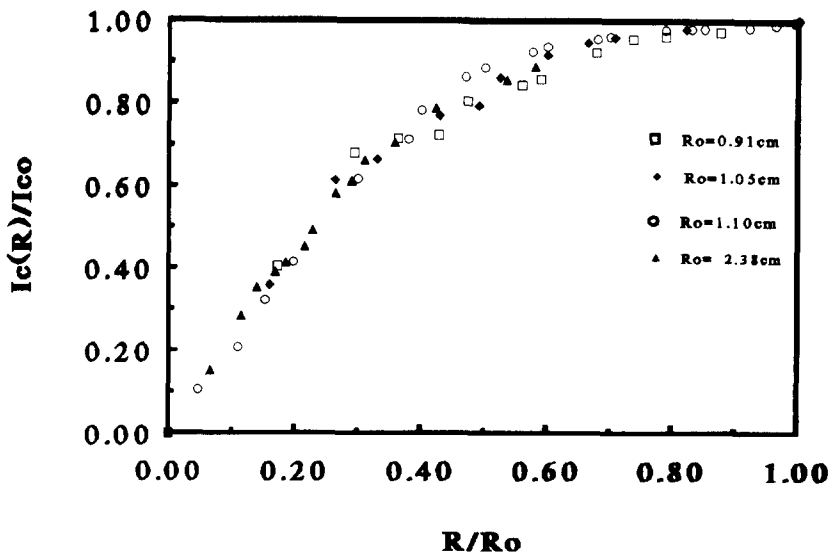


Fig. 1. The normalized critical current $I_c(R)/I_{c0}$ vs. normalized bending radius R/R_0 .

In our bending experiments, an aluminum plate was used as a sample holder and a four-terminal technique, using a Keithley 228 DC power supply and Keithley 181 nanovoltmeter, was employed to determine the transport J_c with a criterion of $1 \mu\text{V}/\text{cm}$ at 77 K. For measurements of the transport J_c , tapes were bent into a circular arc at room temperature, and suffered strains from zero to $\varepsilon = 1.31\%$, which is defined as the ratio of the thickness of the tape to the bending radius R . These experimental results were discussed in the following section.

3. Results and discussion

Fig. 1 shows that the normalized curves $I_c(R)/I_{c0}$ versus R/R_0 gradually deteriorate so it appears that the cracks do not propagate through the entire cross-section. As mentioned above, the magnetic-field behavior of the transport I_c in a bent tape has been extensively studied, and the I_c values do not change at a given field as $\varepsilon < \varepsilon_{\text{irrev}}$. Besides that, $\varepsilon_{\text{irrev}}$ is independent of magnetic field [8]. But, to replot the $I_c(H, \varepsilon)$ curves, an important feature should be

pointed out that the normalized $I_c(H)/I_c(0)$ vs. H curves in Fig. 2 are almost superimposed on the same curve for all bending strains, which is analogous to formulae exploited in the “generalized critical state” model proposed by Xu et al. [14]. The conclusions from Fig. 2 are that the properties of flux pinning in a bent tape do not change, nor does the transport current density J_c . I_c degradation as $\varepsilon > \varepsilon_{\text{irrev}}$ arises from a superconductor fracture, rather than an intrinsic degradation of the superconductor energy gap. Based on the above arguments, it is reasonable to consider that the grain boundaries in a bent tape may be affected and thus the transport current I_c is reduced. I_c is composed of two parts: (1) The Josephson junction tunneling current I_{cs} for the total uncracked regions of grain boundaries (because the uncracked regions correspond to the strongly coupled regions proposed by Shi [12] and the transport current density J_c is unchanged); (2) The current I_{CR} related to the cracked grain boundaries. Cha et al. [10] suggest that the cracked grain boundaries are similar to the brick wall. But the current I_{CR} , which is shared between silver sheath and superconducting brick-wall sections can be neglected for the following reasons.

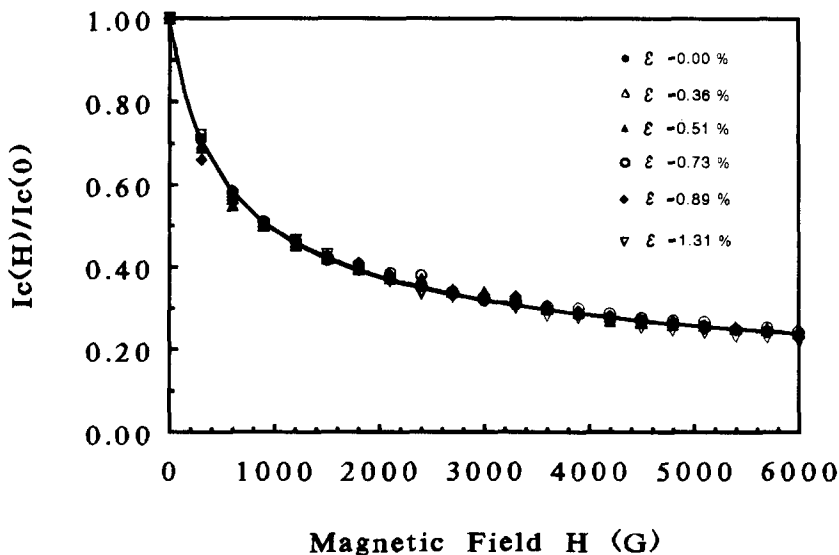


Fig. 2. The normalized critical current $I_c(H)/I_c(0)$ curves are superimposed in the same curve $I_c(H)/I_c(0) = (1 + H/H_0)^{-\beta}$ for all bending strains ε . The H_0 is about 260 G and β is about 0.45.

First, the contact resistance as low as $10^{-14} \Omega \text{ m}^2$ has been reported for Au evaporated on YBCO [15], and recent measurements by Fang [16] on sinter-forged specimens show that the contact resistance is $< 10^{-12} \Omega \text{ m}^2$. Second, the current of the Ag sheath is about $V_c/R_s \sim 10^{-3} \text{ A}$, much smaller than the observed I_c ($\sim 10 \text{ A}$) where V_c is the criterion of $1 \mu\text{V}/\text{cm}$ and R_s is about $10^{-3} \Omega$ is the resistance of the Ag sheath. Therefore, the basic assumption, that the resistance R_s of the silver compared to the interfacial resistance R_i between the silver and the BSCCO is very high, can be taken and ensures that most of the current returns to the superconductor, as described by Cha et al. [10]. In addition to what was mentioned above, if the electric field E of the Ag sheath exceeds the criterion $E_c = 1 \mu\text{V}/\text{cm}$ before the current density J of the superconductor reaches the Josephson junction critical current density J_{cs} of the grain boundaries, the I - V curves should be linear. This is not the case in our experimental results [8], nor in those of Qiang Li et al. [17]. This leads us to believe that the superconductor carries the critical current density J_{cs} . To sum up, the current related to cracked grain boundaries can be neglected and the transport critical current I_c is proportional to the total uncracked regions of grain boundaries and I_{cs} . A “Josephson junction with cracks at the grain boundaries” model is proposed to explain the $I_c(R)/I_{c0}$ versus R/R_0 data.

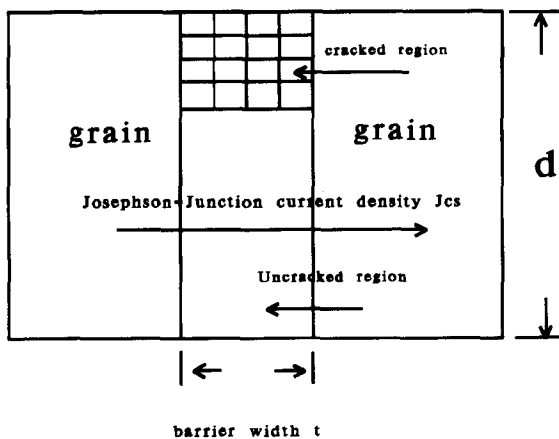


Fig. 3. Schematic diagram of a superconductor including two grains connected by a grain boundary with barrier width t and thickness d . The Josephson junction critical current density J_{cs} only tunnels through the uncracked regions.

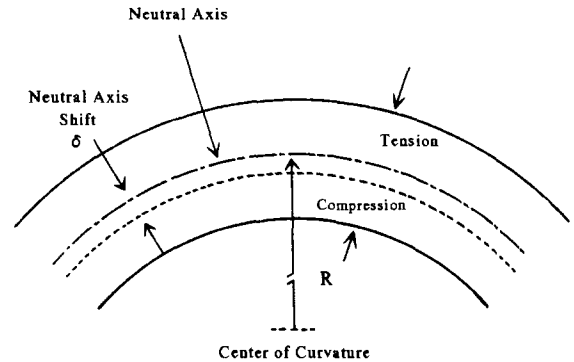


Fig. 4. Schematic diagram of a tape of thickness t bent into a circular form with a radius R of curvature. The neutral axis represents the plane where the bending strain is zero.

The granular superconductor is composed of many random grains; for convenient discussion of our model, we take two of them to replace a superconductor with thickness d , width w , being connected by a grain boundary with a barrier width t , as shown in Fig. 3. The neutral axis, defined as the space where strain is zero, is located at the middle of the superconductor. But, as pointed out by Kaiho et al. [18], when $\epsilon \geq \epsilon_{irrev}$, there is a shift δ of the neutral axis due to crack and the bending strain is larger in the outer parts (tension) of the grain boundary than the inner parts (compression), as shown in Fig. 4. The starting points of our analysis in a simple picture are two assumptions. One of them is that the cracks due to strain, initially occur at the outer parts of the neutral axis of grain boundaries, and gradually distribute through the whole barrier space with increasing bending strain. The other is that the transport current density J_c is unchanged and I_c is only related to the total uncracked grain boundaries at bending radius R .

The strain in the outer parts of no crack at bending radius R will be equal to that in the outer parts of the neutral axis at limited bending radius R_0 , which is determined by the appearance of the initial cracks and can be recorded reliably through acoustic emission. Therefore, the governing equations are

$$\frac{d}{2} \left/ \left(R_0 + d_1 + \frac{d}{2} \right) \right. = \left(\frac{d}{2} - \delta \right) \left/ \left(R + d_1 + \frac{d}{2} - \delta \right) \right. \quad (1)$$

So, we obtain that

$$d - 2\delta = d(R + d_1)/(R_0 + d_1) \cong d(R/R_0), \quad (2)$$

where d_1 is the Ag sheath thickness and is far less than R and R_0 . $d - 2\delta$ is the effective thickness of the uncracked superconducting grain boundaries. Therefore, the Josephson junction tunneling current density J_{cs} is unchanged and the magnitude of the transport critical current is proportional to the total area of unchanged grain boundaries in our model. That is

$$I_c(R)/I_{c0} = (d - 2\delta)wJ_{cs}/(dwJ_{cs}) = R/R_0. \quad (3)$$

However, the granular superconductor is composed of many random grains and the formation of the crack at bending radius R' should obey a probability distribution $f(R')$ of strength of connection among the grain boundaries. Assume $f(R')$ is proportional to $\text{Exp}[-(R' - R_m)^2/R_n^2]$, where R_m is the bending radius, which is the most probable to create cracks at the grain boundaries. The variance R_n characterizes the dispersion of the strength of the grain boundaries about an average value. Hence, in our simple picture, the ratio $I_c(R)/I_{c0}$ is dependent

on the average depth of the uncracked grain boundaries, being

$$I_c(R)/I_{c0} = \int_R^{R_0} \frac{R_0}{R} e^{-\left(\frac{R'-R_m}{R_n}\right)^2} dR' / \int_R^{R_0} e^{-\left(\frac{R'-R_m}{R_n}\right)^2} dR'. \quad (4)$$

The results from our model calculation are plotted in Fig. 5 and the normalized current $I_c(R)/I_{c0}$ versus R/R_0 curve clearly gives a good agreement with the experimental data if the material parameters R_m and R_n are chosen suitably. Of course, the model may be extended to describe the I_c behavior in an applied magnetic field, because the magnetic-field effect and bending effect are independent of each other and it can be expressed by the function $J_c(H, \varepsilon) = J_c(H)K(\varepsilon)$, as we observed.

4. Conclusion

Although the transport properties of a granular superconductor are very complex and dependent on the processing, our theoretical results are in good

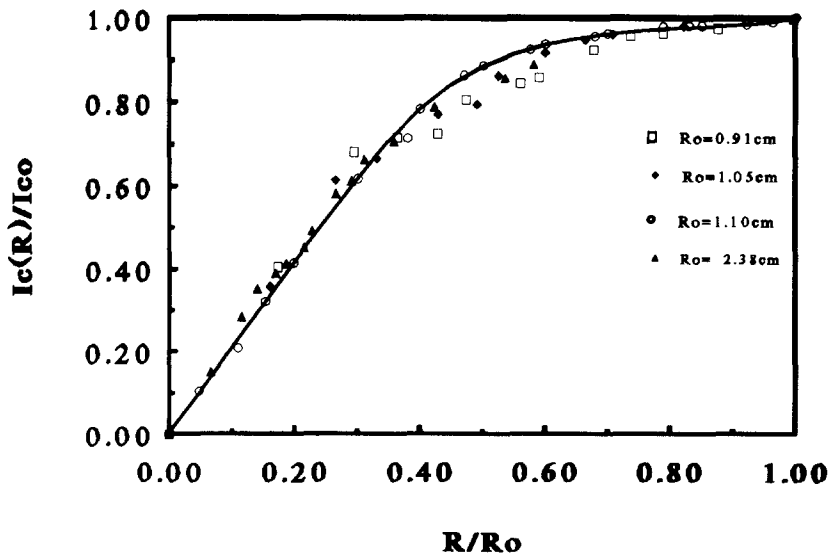


Fig. 5. The theoretical fitting (solid line) gives a good agreement with these experimental results from the samples with different critical bending radius R_0 .

agreement with the experimental data. This suggests that the bending effect be an extrinsic superconducting fracture, not belonging to intrinsic properties. And it is helpful for us to understand the roles of the weak links in the oxide superconducting tape. It is well known that the way to enhance the strain tolerance for the practical application of high- T_c superconductor, is to improve the properties of the Ag sheath, which serves as a crack arrester and provides a region of plastic flow to relieve some of the stress. In this work, we provide another way to enhance the strain tolerance by proper improvement of the material parameters R_m and R_n , i.e. to enhance the connectivity of the grain boundaries and to overcome the weak-link problem.

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