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Microstructure and transport current path in Ag-sheathed $(Bi,Pb)_2$ $Sr_2Ca_2Cu_3O_x$ monofilamentary tapes rolled at different pressures

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Abstract

Ag-sheathed $(Bi,Pb)_2$ $Sr_2Ca_2Cu_3O_x$ monofilamentary tapes have been fabricated by a rolling process including an intermediate sintering step while changing mechanical load. The influence of rolling pressure on microstructure and transport current paths has been investigated through a scanning Hall sensor together with conventional metallurgical studies. An increase in rolling pressure up to 0.27 GPa enhances the transport critical current density J_c through an improvement of grain connectivity. A further increase in the pressure i.e. >0.3 GPa lowers the J_c value significantly by occurrence of a sausaging effect. The optimum rolling pressure is determined by a competition between strengthening grain connectivity and occurrence of sausaging effect. Calculations by modeling current loops reveal a variation in local J_c values along a width direction. The J_c value at the edge is 4–5 times greater than the value at the center. This is consistent with recent strip-cutting experiments.

Keywords: Transport current

1. Introduction

Ag-sheathed $(Bi,Pb)_2$ $Sr_2Ca_2Cu_3O_x$ (Bi2223) tapes are one of the most promising candidates for superconductor applications such as power cables and transformers operating at 77 K because of high critical current densities J_c exceeding 100 A/mm^2 (77 K, 0 T) in long tape-form conductors on the order of 1 km length [1]. Realization of such power devices utilizing Ag-sheathed Bi2223 tapes requires further insight in the understanding of the dominating factors for the J_c value and also in optimizing the processing parameters for tape fabrication.

A significant correlation between the rolling pressure and the J_c value has been recently reported for Ag-sheathed Bi2223 monofilamentary tapes [2], but the reason for this has not been clarified yet. The objective of the study is to make clear the influence of mechanical load under rolling on microstructures and transport current paths in Ag-sheathed Bi2223 monofilamentary tapes.

2. Experimental

The tapes were fabricated by a powder-in-tube method using a rolling process including an intermediate sintering step while changing mechanical load. Calcined powder with a composition of Bi:Pb:Sr:Ca:Cu = 1.84:0.34:2.0:2.2:3.0 was packed into Ag tubes (o.d. 6 mm and i.d. 4 mm). The composites were drawn into round wires of 2 mm in diameter, rolled into tapes 0.2 mm thick, and sintered at 835°C for 100 h in air. Subsequently, they were rolled again into thinner tapes in a single rolling run while changing the mechanical load. Here, the load value under rolling was measured by a load cell equipped with a roller and the rolling pressure was estimated from a conventional expression given in a previous paper [2]. The load values of 37, 192 and 419 kg in the study correspond to the rolling pressure of 0.092, 0.268 and 0.454 GPa, respectively.

The morphology and the microstructures of ceramics core were examined by XRD, SEM and also with an

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image analyzer. Fig. 1 shows the longitudinal cross-sectional views for the samples as a parameter of rolling pressure P. An increase in P lowers the tape thickness of the sample and raises the density of ceramics core, accompanied by changes in both morphology and microstructure. Under low pressure of $P < 0.2$ GPa, co-deformation between Ag sheath and ceramics core takes place [3] and accordingly causes a gradual increase in the geometrical factors such as the aspect ratio of width to thickness for the ceramics core. As can be seen from SEM images for transverse fractures [Fig. 2(a)], there are porous and poorly-oriented platelets grains of ceramics core at this stage. An application of higher pressure under rolling enhances the degree of grain alignment, and accordingly produces dense and highly-aligned microstructures [see Fig. 2(b) and (c)]. High pressure rolling exceeding 0.3 GPa causes the sausaging effect as shown in Fig. 1.

The magnetic field distributions due to trapped currents in a remanent state were measured at 77 K, after removal of external fields perpendicular to a tape surface. The experiment was made by the scanning Hall sensor magnetometer with an active area 50×50 μm described in our previous papers [4]. Magnetic profiles were measured at a fixed distance (∼1 mm) from the tape surface on a two-dimensional area covering the whole surface of the sample. The critical current I_c was determined with a criterion 0.1 μV/mm from current vs

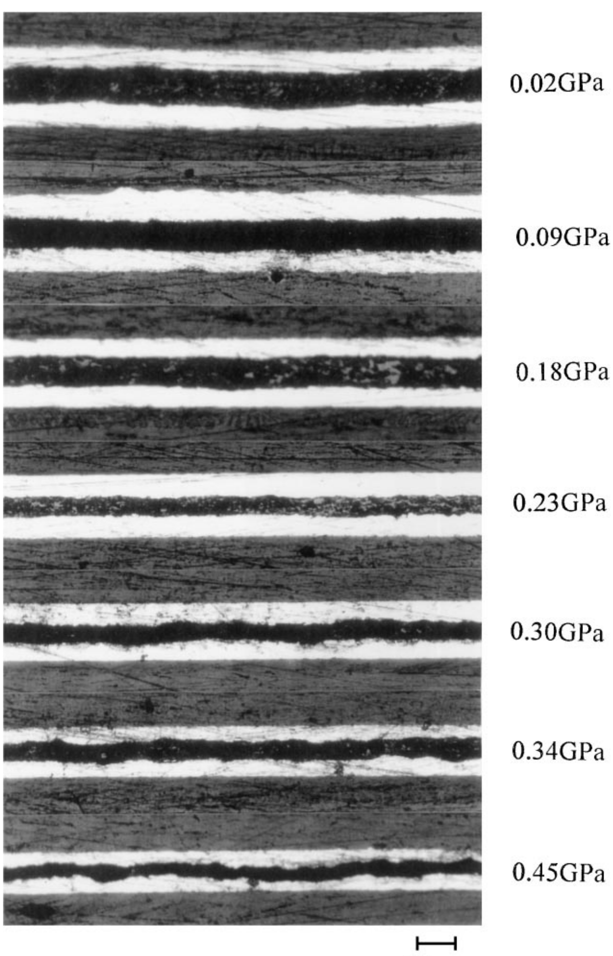

Fig. 1. Longitudinal cross-sectional views of of tape samples rolled at different pressure P.

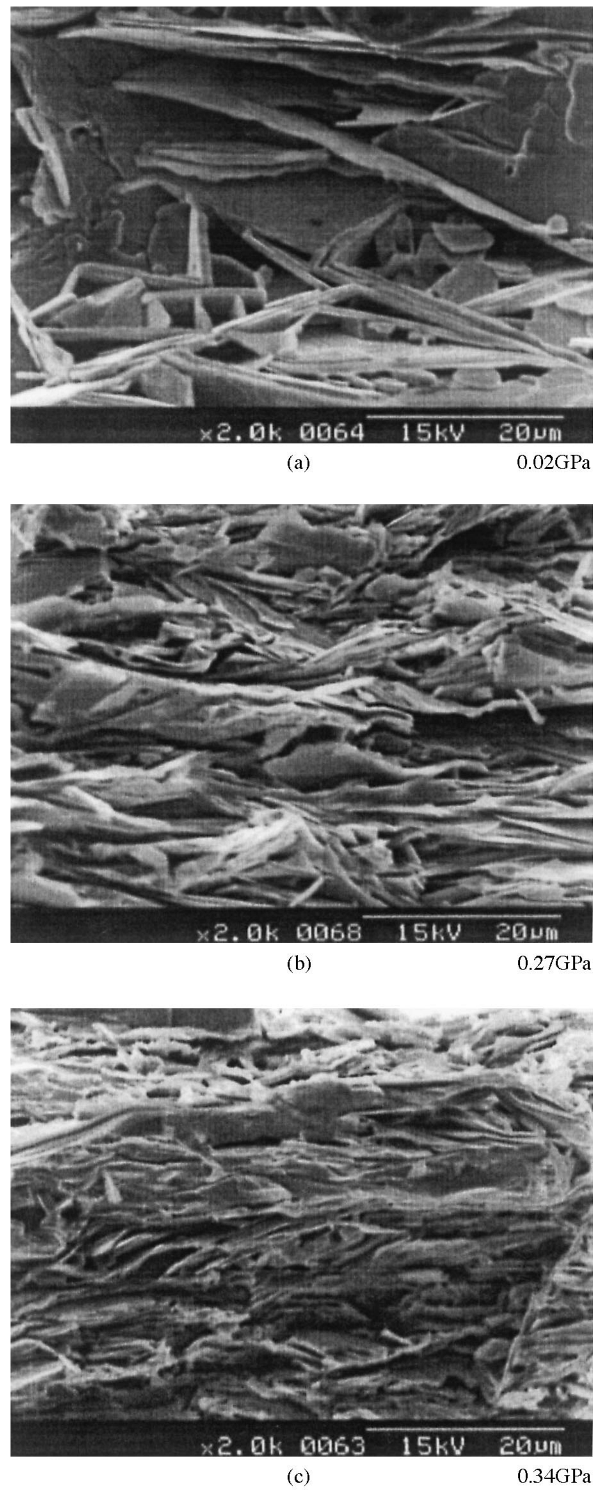

Fig. 2. SEM images for transverse fractures of tape samples rolled at different pressure P.

voltage characteristics at 77 K in self fields and the transport J_c value was estimated from I_c using the cross-sectional area of ceramics core of the sample.

3. Experimental results

The rolling pressure dependence of J_c at 77 K in self fields is shown for the Ag-sheathed Bi2223 mono-filamentary tape in Fig. 3. Note that error bars in the figure are taken as the maximum and minimum values of J_c among five samples prepared under the same conditions and the data show its average for the samples. As can be seen, the J_c value first increases gradually with an increase in rolling pressure for $P < 0.2$ GPa, then rises sharply for 0.2 GPa $< P <$ 0.3 GPa until peaking at $P \sim 0.27$ GPa, and finally drops sharply with a further increase in P for $P > 0.3$ GPa. In conjunction with changes in morphology and microstructure of the ceramics core with rolling pressure (see Section 2), the behavior of J_c in Fig. 1 is discussed.

3.1. Intra-grain current transport for low rolling pressure (P < 0.2 GPa)

The sample subjected to low rolling pressure shows porous and poorly-oriented platelets grains [see Fig. 2(a)], so there are weak links between the grains for the current transport and the current paths should be nearly restricted within the grains themselves. To confirm this conjecture, the trapped magnetic-field distribution in a remanent state, after removal of external field $B_{ex} = 10$ mT perpendicular to a tape surface, is shown for the sample with J_c of 4 A/mm^2 (rolled at $P = 0.02$ GPa) in Fig. 4. Here, the two-dimensional expression $B(x,y)$ with respect to the origin $(x,y) = (0,0)$ corresponding to the tape center is used in the paper to describe the magnetic-field distribution, and the coordinates x and y refer to the width and length directions, respectively. Note that the distribution is insensitive to a variation of B_{ex} for $B_{ex} > 8$ mT, so the sample is in the full critical state [4]. As can be seen from Fig. 4, the result for $B(x,y)$ reflects the core geometry of the sample, and it is nearly symmetric with respect to the origin (i.e. the tape center). The line profile $B(x,0)$ normalized to the value at the center along a width direction is derived from the distribution $B(x,y)$ for the respective samples and the result is shown in Fig. 5. As can be seen, the line profile shows a variation only near the core edge and has a wide plateau around the origin ($x \sim 0$ mm), which is ascribed to the intra-grain current circulation restricted within the grains themselves [4].

Taken together, a gradual increase in J_c with P in Fig. 3 should be ascribed to the slow densification of ceramics core and accordingly a gradual improvement for grain connectivity through co-deformation [3]. This leads to an improvement for the transport current paths in the ceramics core.

3.2. Current path evolution with an increase in rolling pressure (0.2 GPa ⩽ P ⩽ 0.27 GPa)

An application of higher pressure under rolling progresses the densification of the ceramics core and improves the grain connectivity. Highly-oriented and dense microstructures grow up in the ceramics core (see Fig. 2) and the transport currents flow through in the whole part of the core. An improvement for grain connectivity,

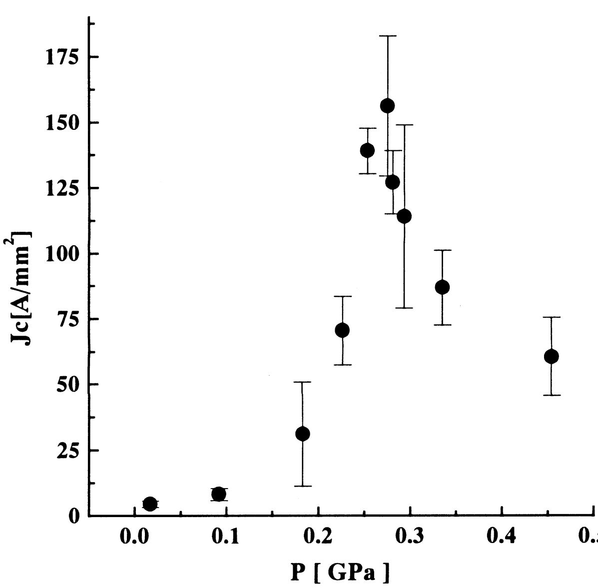

Fig. 3. Transport J_c value at 77 K in self fields as a function of rolling pressure P.

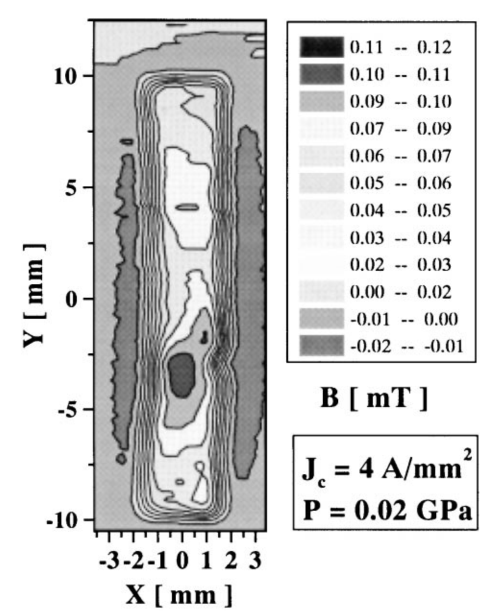

Fig. 4. Trapped magnetic-field distribution for the sample rolled by 0.02 GPa.

accompanied by both grain alignment and densification, should strengthen transport current paths and raise the J_c value sharply, as shown in Fig. 3. This assumption is substantiated by the trapped magnetic-field distribution $B(x,y)$ in a remanent state for the sample with transport J_c of 150 A/mm^2 (rolled by $P=0.27$ GPa) in Fig. 6. Note that the result corresponds to the sample in the full critical state [3]. As can be seen from Fig. 6, the result for $B(x,y)$ is symmetric with respect to the origin in a way similar to the sample with transport J_c of 4 A/mm^2 rolled by $P=0.02$ GPa (see Fig. 4). However, the absolute value of trapped field is by about one order of magnitude greater than the value for the sample with $P=0.02$ GPa. In addition, a field variation in $B(x,y)$ takes place not only near the edge but also near the center, so that the line profile $B(x,0)$ for the sample rolled by $P=0.27$ GPa has a peak at the center $x=0$ mm as shown in Fig. 5. Taken together, all the results show that the distribution $B(x,y)$ for the sample is explained by the inter-grain current transports that flows in the whole part of ceramics core through grain boundaries.

It is worthwhile mentioning that an increase in P from 0.2 to 0.27 GPa sharpens the peak at around the center $x=0$ mm in the line profile $B(x,0)$ shown in Fig. 5. This suggests a variation of the current capacity from place to place along a width direction, which will be discussed in Section 4.

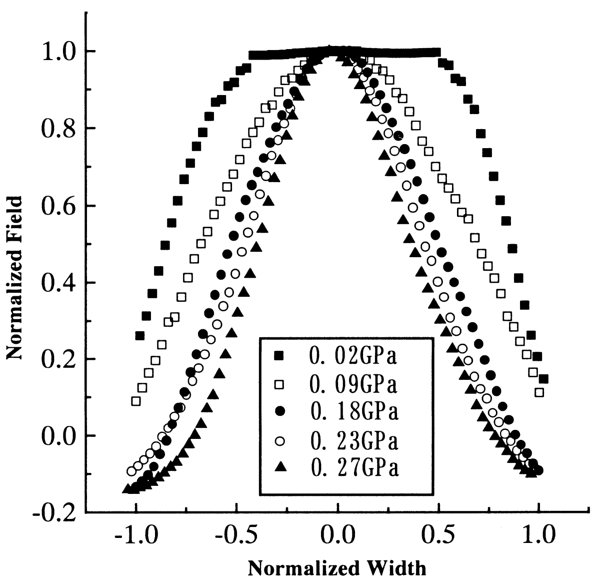

Fig. 5. Line profile along a width direction for samples rolled by different pressure P.

3.3. *The occurrence of sausaging effect with a further increase in rolling pressure (P > 0.3 GPa)*

As rolling pressure increases further exceeding 0.3 GPa, the densification of ceramics core proceeds to the extremity and causes the sausaging effect, as shown in Fig. 1. It should disturb the transport current flow and degrades J_c value significantly. As can be seen from Fig. 7, the sample with J_c of 88 A/mm^2 (rolled by 0.34 GPa) shows a distorted and asymmetric magnetic profile. The inter-grain current transports that yield high values of trapped fields in $B(x,y)$ are localized within the restricted region of the ceramics core, so that there are no current transports flowing in the whole part of ceramics core.

The present study shows the existence of an optimum rolling pressure for tape fabrication that is determined by a competition between strengthening grain connectivity and occurrence of the sausaging effect. About the magnitude of the optimum rolling pressure, the

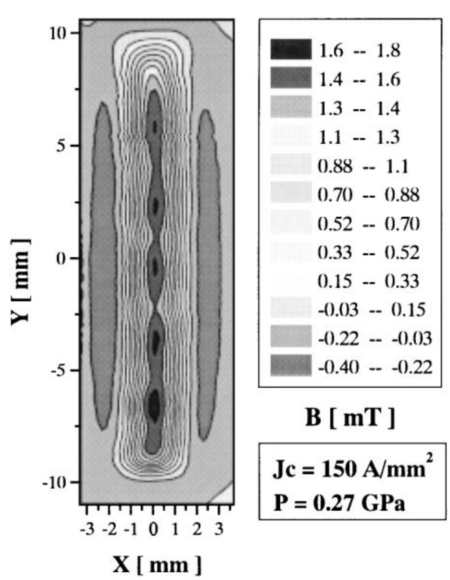

Fig. 6. Trapped magnetic-field distribution for the sample rolled by 0.27 GPa.

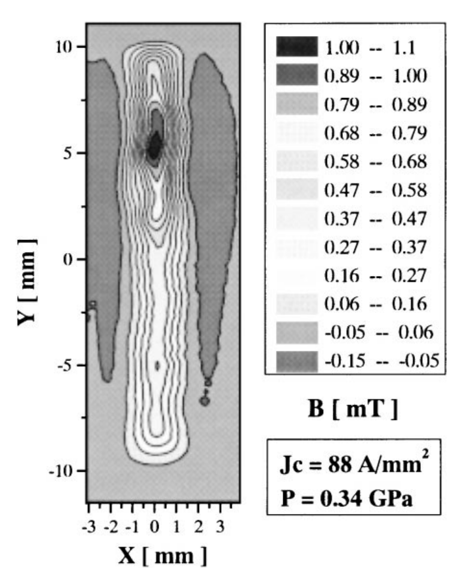

Fig. 7. Trapped magnetic-field distribution for the sample rolled by 0.34 Gpa.

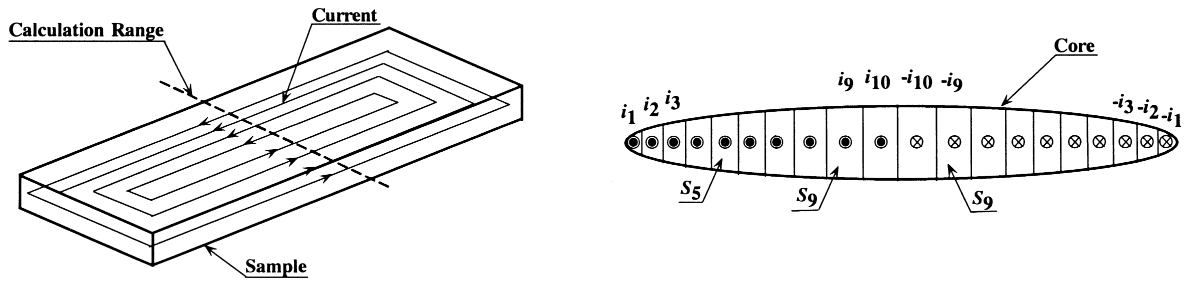

Fig. 8. Schematic diagram for analyses using 10 rectangular current loops.

value of $P = 0.27$ GPa obtained here is smaller than the value of 0.67 GPa by a previous paper [2]. The reason for the difference has not been clarified yet, but it may come from the difference in the composition of co-precipitation powder, the powder density packed into Ag tubes, the diameter of the round wire before rolling, the tape width, etc.

4. Discussion

The result for the line profile $B(x,0)$ along a width direction shown in Fig. 5 suggests a variation of current capacity from place to place along a width direction, as reported by strip-cutting experiments on Ag-sheathed Bi2223 monofilamentary tapes [5]. In this section, we make numerical calculations on the field distribution $B(x,0)$ due to trapped currents along a width direction by modeling current loops and obtain the J_c distribution along a width direction by comparing the calculation result with the measured profile $B(x,0)$. We discuss how the distribution of J_c is influenced by an increase in rolling pressure that progresses the current path evolution in the ceramics core. We note here that the discussion is restricted to the pressure range of $P \leqslant 0.27$ GPa, because the high pressure rolling exceeding 0.3 GPa causes the sausaging effect and accordingly produces the distorted and asymmetric magnetic profile.

For calculations, we assume 10 rectangular current-paths as the surface currents on the core [see Fig. 8] and regard the current values (i_1, i_2, …, i_{10}) for the respective paths as adjustable parameters that are determined by the fit to the profile $B(x,0)$. The difference Δ in the absolute value of magnetic field between calculation and experiment is obtained and summed up for all measuring points along a width direction. A minimization procedure for the difference Δ, while changing current values (i_1, i_2, …, i_{10}) for the respective paths, determines the final current values of the paths for the best fit and yields a theoretical curve for the distribution $B(x,0)$. A comparison between calculation field and measured profile for $B(x,0)$ is typically shown for the sample with J_c of 150 A/mm^2 (rolled at 0.27 GPa) in Fig. 9, where there is a nice agreement between them. The same story

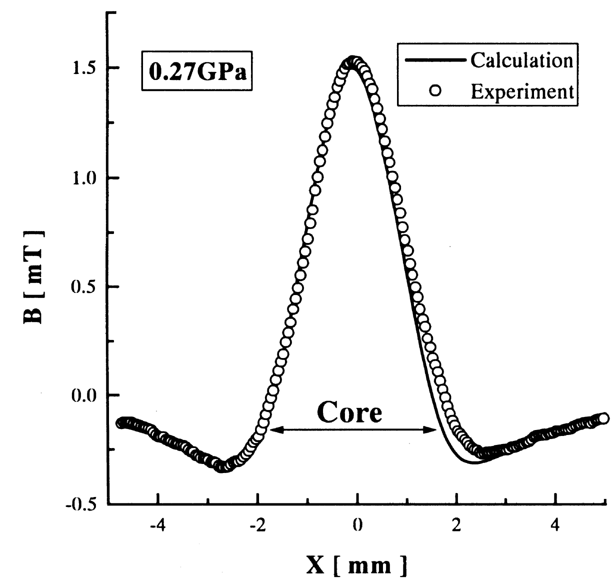

Fig. 9. A comparison between calculation field and measured line profile on the sample rolled at 0.27 GPa.

stands for other samples rolled at different pressure for $P \leqslant 0.27$ GPa. Cross-sectional areas (S_1, S_2, …, S_{10}) occupying the respective current paths [Fig. 8] are measured for the actual ceramics core of the sample by an image analyzer, to convert the respective currents (i_1, i_2, …, i_{10}) to the J_c distribution.

The results for the distribution of J_c for the samples rolled at different pressure for $P \leqslant 0.27$ GPa are shown in Fig. 10. Note that the difference Δ in the fitting procedure for the respective samples is very small (at most 0.35 mT for the sample rolled by 0.27 GPa), which is never obtained from the homogeneous J_c distribution in the core. As can be seen from Fig. 10, a variation of J_c along a width direction stands for all samples investigated, independent of rolling pressure up to 0.27 GPa. The sample with J_c of 4 A/mm^2 (rolled at 0.02 GPa) has the local J_c value of 80 A/mm^2 only at the edge but nearly 0 A/mm^2 in the interior of the core, so that the transport current flows only at the edge.

An increase in P enhances the local J_c value at the edge and gives a finite value even in the interior of the core. The sample with transport J_c of 150 A/mm^2 (rolled

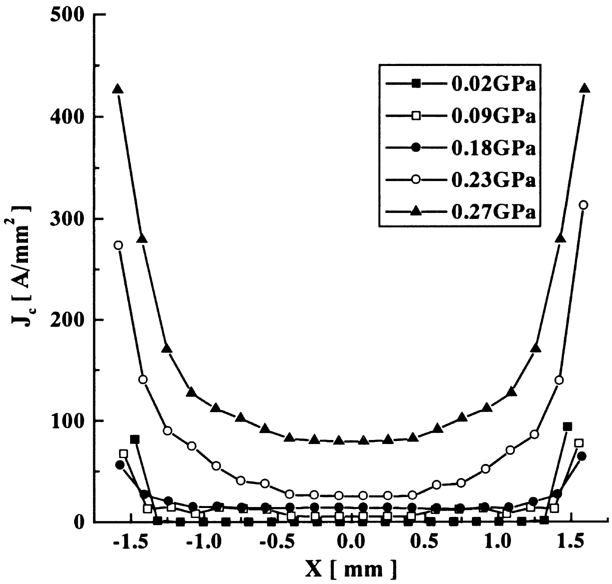

Fig. 10. Distribution of local J_c along a width direction for samples rolled at different pressure P.

at 0.27 GPa) shows the local J_c of 440 A/mm^2 at the edge that is about 4–5 times greater than the value of 100 A/mm^2 at the center. This is consistent with strip-cutting experiments on Ag-sheathed Bi2223 tapes [5].

Judging from SEM images on core surfaces, the variation of local J_c value in ceramics core can be ascribed to the difference of microstructures going from the edge to the center along a width direction. The degree of grain alignment and also the grain size in the microstructure at the edge is higher than that at the center, since highly-oriented Bi2223 grains grow up from the Ag/ceramics interface to the interior of the superconductor core during the thermo-mechanical treatments [3].

5. Summary

The influence of rolling pressure on microstructure and transport current paths have been investigated on Ag-sheathed Bi2223 monofilamentary tapes rolled by different pressure, through a scanning Hall sensor together with metallurgical studies.

Enhancement of J_c with an increase in rolling pressure up to ~0.3 GP is ascribed to the evolution in transport current paths. Degradation in the J_c value with a further increase in the pressure exceeding 0.3 GPa is caused by the occurrence of a sausaging effect. The optimum rolling pressure during rolling is determined by a competition between strengthening grain connectivity and occurrence of the sausaging effect.

Numerical calculations by modeling current loops give a variation in current capacity along a width direction in the core. The local J_c value at the edge is 4–5 times greater than the value at the center, that is consistent with strip-cutting experiments [5]. The present study shows that a scanning Hall sensor can be used as a powerful tool to obtain information on the critical current distribution in the core of Ag-sheathed Bi2223 monofilamentary tape without destroying the sample.

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