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High-speed scanning Hall-probe microscopy for two-dimensional characterization of local critical current density in long-length coated conductor

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Abstract

We have succeeded in significant improvement in measuring speed of scanning Hall-probe microscopy for two-dimensional characterization of local critical current density in a coated conductor. A typical measuring speed was 36 m/h with a spatial resolution of 1 mm in longitudinal direction and 40 micrometers in width direction while the combination of the speed and the resolution could be changed on demand. This was 200 times faster than the speed of our previous system, and could be applicable to a long-length conductor. From the magnetic field distribution in a remanent state, we could estimate in-plane distribution of local critical current density in nondestructive manner. For example, we could confirm almost homogeneous local properties in a GdBCO coated conductor, and at the same time we detected some defects in the edge of the conductor. Furthermore, we could also confirm the applicability of this method to a multifilamentary coated conductor. These results would be helpful for (1) quality control of an original conductor, (2) that of a finer conductor slit from a wider one, (3) that of a multifilamentary conductor, (4) understanding of macroscopic current transport properties, (5) investigating a typical statistics correlated with the fabrication process, and so on.

Keywords: coated conductor; critical current distribution; scanning Hall-probe microscopy

1. Introduction

$REBa_2Cu_3O_{7-\delta}$ (REBCO, RE: rare earth) coated conductors (CCs) have very high performance in critical current density as well as its magnetic field dependence. Furthermore, they have possibilities for AC losses reduction by slitting or striating to a finer CC or a multifilamentary CC. From these advantages, they are strongly expected for high-filed applications as well as electric power applications.

On the other hand, they sometimes have inhomogeneous distribution in their superconducting properties. This means that some characterization methods for investigating such inhomogeneity is indispensable for their further

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performance improvement and quality control necessary in the stage of industrial production. For example, magneto-optic imaging (MOI) [1, 2] is a powerful method for visualizing local inhomogeneity in CCs with a very good spatial resolution. TAPESTAR™ [3, 4] is a well-known method for estimating longitudinal distribution of critical current in CCs.

In particular, we have been developing a characterization method using scanning Hall-probe microscopy (SHPM) [5]. The advantage of this method is capability for estimating in-plane distribution of critical current density. This information would be very helpful for (1) quality control of an original conductor, (2) that of a finer conductor slit from a wider one, (3) that of a multifilamentary conductor, (4) understanding of macroscopic current transport properties, (5) investigating a typical statistics correlated with the fabrication process, and so on.

However, the characterization speed of our SHPM was relatively slow in the past. For example, it took one hour to take an image of 18-mm-long CC with a spatial resolution of 100 μm. This cannot be applicable for the characterization of long CCs. From this point of view, we tried to dramatically improve the characterization speed of SHPM by using high-speed scanning stage for a Hall probe as well as a technique for noise reduction.

2. Method

2.1. Principle for the estimation of in-plane distribution of critical current density

When a sufficiently large magnetic field is applied to a CC, current flows at critical current density to shield such a magnetic field almost in all area of the CC. Similarly, after a sufficiently large magnetic field is removed, current flows at critical current density to trap such a magnetic field. This means that we can estimate in-plane distribution of critical current density from that of magnetic field around a CC. The SHPM is utilized to obtain such a magnetic field distribution. The details of the principle were already reported in our previous paper [5].

There would be two methods for obtaining magnetic field distribution by a Hall sensor. One is using a laterally-aligned multi-channel sensor only scanning in longitudinal direction. This would achieve very high-speed mapping of magnetic field distribution, and is actually adopted for TAPESTAR™ [3, 4]. However, the spatial resolution in width direction is limited by the distance between the adjacent channels. This may be critical in the characterization of a finer CC or a multifilamentary CC. From this point of view, we decided to scan a single-channel sensor both in width and longitudinal directions.

2.2. High-speed scanning stage for a Hall probe

The key issue of this study is to improve the measuring speed of magnetic field distribution. Fig. 1 shows a photograph of the developed SHPM system. The top of the triaxial precision stage is the high-speed scanning stage for a Hall probe. This linear servomotor stage can move the Hall probe at 10 times per second in width direction of a CC. At the same time, a precision stage at the bottom moves the stage in length direction. As a result, scanning speed itself was improved to be 200 times faster than that of our previous system, e.g., 3.6 m/h with a spatial resolution of 40 μm in width x 100 μm in length directions (hereinafter called Condition (I)), 36 m/h with 40 μm in width x 1000 μm in length directions (hereinafter called Condition (II)), and so on. The combination of the scanning speed and spatial resolution can be changed within a certain sampling rate for measuring magnetic field. The stage and the Hall probe were rigid enough to keep the distance between the Hall sensor and the sample. We have not estimated the precise vibration yet; however the error of the distance seems to be less than 50 μm at the maximum judging from an observation by a fixed camera. A typical distance between the Hall sensor and the sample is 300 μm for this system.

2.3. Noise reduction

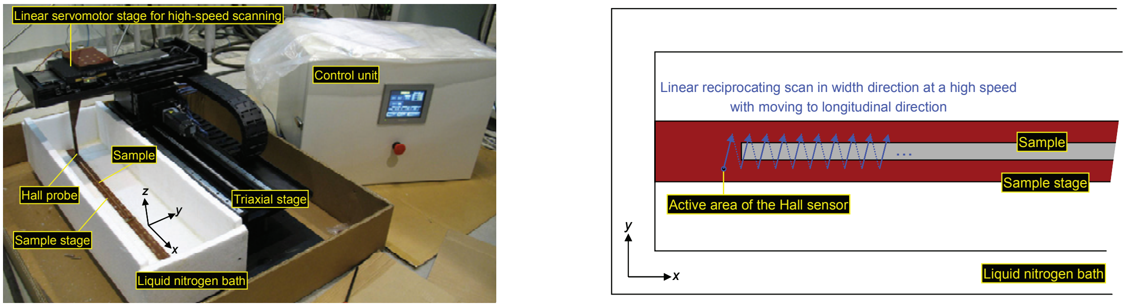
When the scanning speed was relatively slow as in our previous system, we could reduce the noise in the signal from the Hall sensor by taking a moving average. Fig. 2 shows such an effect by the averaging: from (a) to (b). However, in case of high-speed scanning, we cannot take a sufficient averaging because time per measuring point becomes much shorter at a same sampling rate. Then, the signal from the sensor still includes very large noise: (c) which could not be used for the characterization. On the other hand, we could found that noise could be greatly suppressed by taking a signal through a lock-in amplifier from an AC current biased Hall sensor: from (c) to (d). The AC bias current of 10 kHz was used in this study. This was also a key technology for the improvement of the measuring speed of the SHPM.

3. Results and discussion

Fig. 3 shows the results obtained for a 5-mm-wide GdBCO CC in Condition (I): 3.6 m/h with a spatial resolution of 40 µm in width x 100 µm in length directions. The distribution of magnetic field, B_z, was obtained in a remanent state where the CC was magnetized by a permanent magnet. The distribution of sheet current density, J, was analytically calculated from it [6]. The current flows in $+x$ direction in the lower part and in $-x$ direction in the upper part to trap a magnetic field in $+z$ direction. It can be found from the distribution, the CC has almost homogeneous properties. However, it is also showed that the upper part has relatively higher performance than the lower part does. Furthermore, there seem to be some defects at the edges of the sample as indicated by arrows. In this way, we could characterize in-plane inhomogeneity in a CC by the developed system as was succeeded by the previous system. Only the characterization speed has become 200 faster at the same order in spatial resolution.

Since the characterization speed of Condition (I) might be a little bit slow for a long CC, we also tried a measurement in Condition (II) 36 m/h with a spatial resolution of 40 µm in width x 1000 µm in length directions. Fig. 4 shows the result. The spatial resolution in length direction was sacrificed for the characterization speed. However, almost all the information in Condition (I) could be obtained: almost homogeneous properties, higher performance in the upper part, and some defect at the edges. This indicates the applicability of this characterization method to a long CC from the point of view of characterization speed.

Furthermore, we applied this method for a 5-mm-wide multifilamentary CC with 3 filaments. Fig. 5 shows the results. The above-mentioned current flow was obtained for each filament. As a result, we could find almost homogeneous properties with some part having low properties. In this way, this method could be applied to a multifilamentary CC. This is an important advantage of this method.



(a) (b)

Fig. 1. (a) photograph of the scanning Hall-probe microscopy system; (b) schematic diagram of the scanning trace of the Hall-sensor.

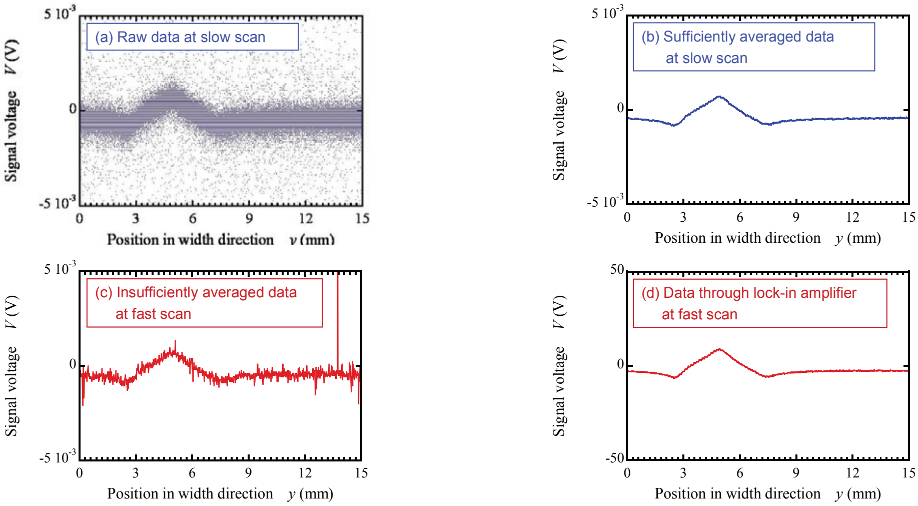


Fig. 2. Effect of the noise reduction on a lateral distribution of remanent magnetic field in a 5-mm-wide CC: (a) raw data at a slow scan; (b) sufficiently averaged data at a slow scan; (c) insufficiently averaged data at a fast scan; (d) data through a lock-in amplifier at a fast scan.

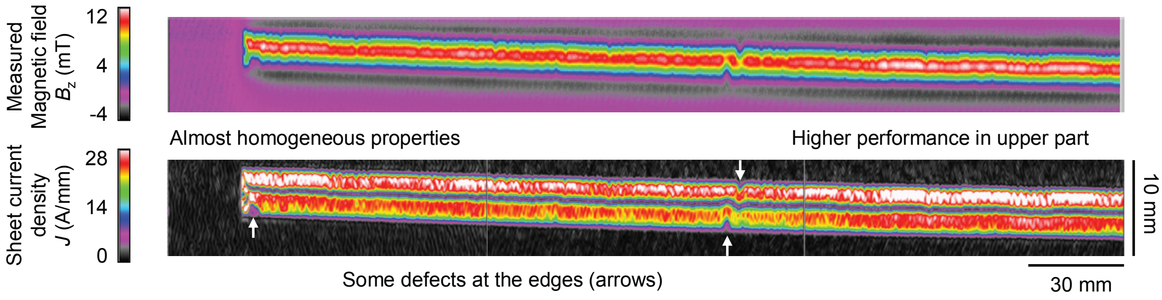


Fig. 3. Results obtained for a 5-mm-wide CC with characterization speed of 3.6 m/h and mapping resolution of 40 μm^{w} x 100 μm^{l}.

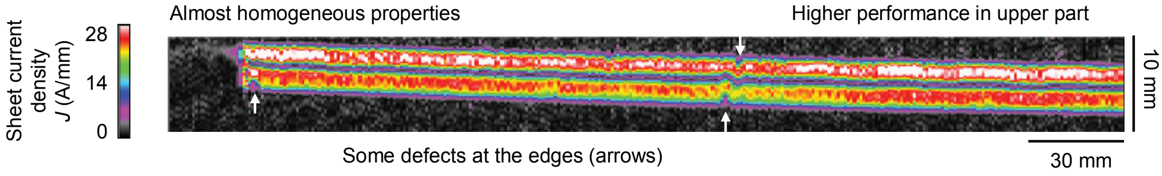


Fig. 4. Results obtained for a 5-mm-wide CC with characterization speed of 36 m/h and mapping resolution of 40 μm^{w} x 1000 μm^{l}.

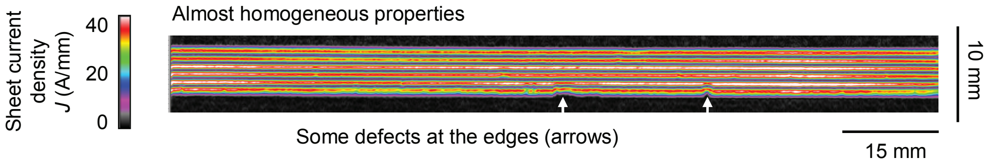


Fig. 5. Results obtained for a 5-mm-wide multifilamentary CC with 3 filaments.

4. Conclusion

We succeeded in significant improvement in measuring speed of scanning Hall-probe microscopy for two-dimensional characterization of local critical current density in a coated conductor. A typical measuring speed was 36 m/h with a spatial resolution of 1 mm in longitudinal direction and 40 micrometers in width direction while the combination of the speed and the resolution could be changed on demand. This was 200 times faster than the speed of our previous system, and could be applicable to a long-length conductor. We are developing reel-to-reel conductor carrying system for this method to characterize a much longer coated conductor as a next work.

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