FLUX PINNING BY 211 PRECIPITATES IN MELT-PROCESSED $\text{YBa}_2\text{Cu}_3\text{O}_x$ *

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Abstract--Magnetic hysteresis data have been taken at 4.2 and 50 K over a wide range of magnetic fields on melt-textured (MT) and quench-melt-growth-processed (QMGP) $\text{YBa}_2\text{Cu}_3\text{O}_x$ samples with 6 vol.% of Y_2BaCuO_x (211). In order to obtain accurate comparisons of the intragranular critical current densities, the magnetization measurements were performed on finely powdered samples, the average particle size of which was less than the grain size of the original sample. The QMGP samples exhibited substantially larger hysteresis, indicating significantly enhanced flux pinning at these temperatures. At 4.2 K and 5 T, J_c increase from $4 \times 10^4 \text{ A/cm}^2$ in the MT sample to $5.5 \times 10^5 \text{ A/cm}^2$ in the QMGP sample. A possible pinning mechanism related to the observed hysteretic behavior is discussed.

I. INTRODUCTION

Flux pinning mechanisms have been extensively studied for the $\text{YBa}_2\text{Cu}_3\text{O}_x$ (123) system. It has been claimed that there are three types of major pinning centers in this material: (a) twin boundaries, (b) oxygen vacancies, and (c) Y_2BaCuO_x (211) phase. Twin boundary pinning has been found in transport measurements. However, the pinning strength is not sufficiently large to account for the high intragranular critical current density, J_c , observed in 123. Although there has been some evidence that indicates pinning associated with oxygen vacancies, no direct microscopic observation has been done that could correlate flux pinning behavior with this type of defect. Whether 211 particles can contribute to flux pinning has been controversial. Murakami first claimed that, by adding additional 211 phase in quench-melt-growth-processed (QMGP) 123, critical current density was significantly increased [1]. Later, Jin et al. repeated the experiment, but using a somewhat different technique, melt-texturing (MT), and reported that 211 phase did not at all contribute to flux pinning [2]. In this study, we report magnetization experimental data of both MT and QMGP 123 samples at various temperatures up to 5 T. We show that 211 precipitates can act as strong pinning centers when they have the right morphology.

II. EXPERIMENTAL PROCEDURE

The powder for the 6% 211 additions was obtained from a commercial source. For some of the specimens, the 211 was mechanically mixed into 123 powder, and 20 g of the combined powder were cold-pressed in a 31.8 mm cylindrical die. The conventionally melt-textured samples were fabricated from sintered bars. The bars were cold-pressed in a 50 mm by 7.6 mm steel die. The bars were placed on Al_2O_3 plates and

sintered for 3 h at 980°C in O_2 . The sintered bars were melt-textured in air in a vertical orientation. The texturing heat treatment was as follows: rapid insertion into a furnace at 1150°C , holding for 0.2 h, cooling for 0.1 h to $\approx 1050^\circ\text{C}$, cooling to 950°C at 1°C/h [3].

The quench-melt-growth-processed (QMGP) 123 with 6% 211 was processed by the method devised by Murakami [1]. The Murakami method features quenching from above 1200°C . At this temperature, liquid and Y_2O_3 are present. Subsequent conventional melt-texturing is effective in limiting the growth of the 211 precipitates. The final microstructure generally consists of 123 with much of the 211 being present as rounded precipitates that range in diameter from less than 1 μm to a few micrometer.

Small portions from each specimen were crushed with an agate mortar and pestle. The specimens were first cooled in liquid N_2 to minimize the formation of dislocations during crushing. All of the powders were annealed at 450°C in O_2 for 4 h. Powder particle sizes were compared by scanning electron microscopy (SEM).

The magnetic-hysteresis measurements were performed on a commercial vibrating-specimen magnetometer containing a superconducting magnet in a gas-flow-type cryostat.

III. RESULT AND DISCUSSION

Figure 1 shows that the microstructure of MT 123 consisted of large, elongated 123 grains and large 211 particles (Fig. 1a). The QMGP 123 consisted of some intragranular BaCuO_2 and CuO and 123 grains that contained a nearly uniform dispersion of primarily submicrometer 211 particles. This dispersion of 211 particles is shown in Fig. 1b, a polished section of an individual particle of the crushed QMGP powder.

Representative data at 4.2 K are shown in Fig. 2. It is noted that the mass of each sample was $\approx 100 \text{ mg}$ and that the average particle sizes of the powders were similar. The hysteresis loop of the QMGP sample is substantially larger than that of the MT 123 sample.

By applying a simplified Bean model ($J_c = 30\Delta M/d$, where ΔM is the hysteresis difference and d is the particle size), we have calculated the critical current densities which are shown in Figure 3. As can be seen in Figure 3, at 4.2 K and 5 T, J_c increases significantly from $4 \times 10^4 \text{ A/cm}^2$ in the MT sample to $5.5 \times 10^5 \text{ A/cm}^2$ in QMGP sample. Considerable J_c

Fig. 1 Secondary electron SEM Photographs : (a) MT 123 consisting of larger 123 grains and 15-100 μm spherical 211 aggregates, and (b) single particle of QMGP 123 after crushing. Fine, well-distributed 211 particles are evident in the 123

enhancement is also achieved in the QMGP sample at 50 K, as indicated in Figure 3

These measurements constitute direct evidence for the benefits to flux pinning provided by submicrometer, well-distributed 211 particles. There were no clear indications that the large 211 particles in 123 were effective in pinning flux

Fig. 2 Magnetic Hysteresis at 4.2 K for Melt-Textured MT 123 and QMGP 123 Sample.

lines. This result is in agreement with other work [1]. Particles $\approx 50 \mu\text{m}$ in diameter would not be expected to pin flux directly and may not, in fact, add substantially to other defect concentrations. The interfaces between 123 and 211 particles may in some instances be highly strained because of the lattice and thermal-expansion incompatibilities between these two phases. Linear and planar faults are likely to result, and there is a growing body of evidence that dislocations, stacking faults, and planar boundaries can contribute to flux pinning in high-temperature superconductors. However, the distances between the large 211 particles were also large. Possible benefits to pinning from the defects in proximity to the 211 particles will not be present throughout the samples because of the separation of the 211 particles. It seems to be unlikely that 211 particles substantially larger than 5-10 μm can be beneficial to 123 for flux pinning. The 211 additions will, however, modify the growth kinetics of the 123 melt-textured grains.

Fig. 3 J_c vs. Field at 4.2 K and 50 K for MT 123 and QMGP 123 Sample.

It has been reported from Transmission electron microscopy studies that all melt-textured 123 contains high concentrations of dislocations and stacking faults, even in the absence of added 211 [3,4,5]. These defects appear to be related to the improved intragranular J_c values of melt-textured 123 compared with sintered 123. If 211 precipitates increase these concentrations, effective pinning will require that the precipitates be very finely distributed. The majority of the 211 particles in the QMGP used in this study were submicrometer and were well distributed. They may therefore have been responsible for the improved pinning observed at 4.2 and 50 K and, at low fields, at 77 K.

Although the specific pinning mechanisms cannot be identified with certainty for the melt-processed 123 with addition of 211, a qualitative pinning picture can be discussed based on previously proposed pinning models [6]. There are several factors that are related to pinning. The dimension of the pinning centers, a , and the spacing, l , between them are essential in determining what type of pinning is likely to occur in a system. If the a and l are greater than the penetration depth, λ , the local induction, B , will be affected by the nearby pinning centers, which have a different magnetic induction. As flux motion occurs, the different induction generated in both the superconducting matrix and the pinning centers can cause further pinning, which is often referred to as magnetic pinning [6]. The pinning strength is proportional to the difference in B . Therefore, this difference in B would be greatest when the pinning centers are nonsuperconducting, such as the 211 phase. For 123, λ is about 0.1 μm , which is smaller than a (about 0.5 μm) and l (5–10 μm), and thus magnetic pinning will probably dominate in QMGP materials.

IV. CONCLUSIONS

It was found that flux pinning can be significantly enhanced by introducing fine 211 precipitates into a 123 matrix, a result that agrees well with the results reported by Murakami et al. [1]. Although the dimension of the pinning centers ($\approx 0.5 \mu\text{m}$) was much larger than the coherence length of the superconductor, flux pinning could still be effective, possibly because of faults near the 211 or because of magnetic pinning associated with the fine 211 particles in the QMGP 123.

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