Flux Pinning Enhancement and Irreversibility Line of Sm doped YBCO Superconductor by Zone Melt Growth Process

So-Jung Kim[a]
Department of Electrical and Electronic Engineering, Dong Hae University, Donghae, Gangwon 240-713, Korea

[a]E-mail : sjkim@donghae.ac.kr

(Received February 25 2004, Accepted April 7 2004)

High T_c $(Sm/Y)_{1.8}Ba_{2.4}Cu_{3.4}O_{7-\delta}$ [(Sm/Y)1.8] superconductor, a combination of Y and Sm(50% each), was systematically investigated by the zone melt growth process. A sample prepared by this method showed well-textured microstructure, and $(Sm/Y)_2BaCuO_5$ [(Sm/Y)211] inclusions were uniformly dispersed in large $(Sm/Y)Ba_2Cu_3O_y$ [(Sm/Y)123] matrix. The sample showed a sharp superconducting transition at 91 K. The magnetization measurements of the (Sm/Y)1.8 sample exhibited the enhanced flux pinning, compared with $Y_{1.8}Ba_{2.4}Cu_{3.4}O_{7-\delta}$ (Y1.8) sample without Sm. Critical current densities of (Sm/Y)1.8 sample was 3.5×10^4 A/cm^2 at 1 T and 77 K.

Keywords : $(Sm/Y)_{1.8}Ba_{2.4}Cu_{3.4}O_{7-\delta}$, Zone melt growth, $(Sm/Y)_2BaCuO_5$, Flux pinning

1. INTRODUCTION

In order to achieve a large critical current density in a magnetic field, it is necessary to introduce strong pinning centers into the superconductors. In bulk YBCO compound, however, critical current densities are limited by weak links between grain boundaries. Directional melt texturing is a good fabrication method to eliminate the weak links and obtain large grain with good alignment so as to increase critical current density[1-3].

Additionally, the melt-textured high T_c superconductor enables flux pinning to improve by introducing fine dispersion of second phase precipitate, such as Y_2BaCuO_5(Y211), which acts as pinning center[4,5]. The OCMG(oxygen-controlled melt-growth)-processed REBCO(RE: Nd, Sm, etc.) superconductors have been reported to increase T_c(K) and critical current density(J_c)[6,7]. It is remarkable that flux pinning of melt-textured SmBCO($SmBa_2Cu_3O_{7-\delta}$) is larger than that of melt textured YBCO($YBa_2Cu_3O_{7-\delta}$) in high field region[8]. An important drawback of these materials is, however, that the real composition is $RE_{1+x}Ba_{2-x}Cu_3O_{7-\delta}$, which has relatively large radii, easily substitutes for the Ba site and then leads to the depression of T_c when the solidification is performed in air.

We have developed a fabrication method for synthesizing homogeneous (Sm/Y)1.8 phase, which we got from the substitution of Sm for the half of Y and by the zone melt growth process in air[9,10]. This material provides sharp superconducting transition near 90 K and strong flux pinning. In this paper we report on the analysis of microstructure, magnetization measurements and critical current densities in the melt-textured (Sm/Y)1.8 samples prepared by this method.

2. EXPERIMENTAL

Directionally melt texturing process for fabricating (Sm/Y)1.8 superconductor containing (Sm/Y)211 second phase is as follows. Precursor powders prepared from raw materials of Sm_2O_3, Y_2O_3, $BaCO_3$, and CuO powders were mixed for a nominal composition of (Sm/Y)1.8 and calcined at 900 °C for 30 h twice in air with intermediate grinding. The calcined powders with 1 wt.% CeO_2 were milled with attrition for 6 h in acetone using zirconia balls with a rotation speed 450 rpm. The (Sm/Y)1.8 powders milled with attrition were dried in air, and then isostatically pressed into a small cylindrical type. The pre-heated(930 °C, 5 h) (Sm/Y)1.8 rod samples showed directionally melt-textured growth to obtain a well oriented specimen in a zone melting furnace. An unidirectional solidification was obtained by moving the sample upward through a hot zone(1100 °C) at a rate of about 3 mm/h. The post-heat treatment was performed at 450 °C oxygen gas atmosphere for 100 h in a separate furnace. To analyze the effect of Sm substitution, another $YBa_{1.8}Ba_{2.4}Cu_{3.4}O_{7-\delta}$(Y1.8) sample without Sm substitution was also fabricated by the same procedure. Each unidirectional sample of (Sm/Y)1.8 and Y1.8 was cleaved into smaller sections (2~3 mm long) for characterization. The microstructure of the sample was characterized by SEM and TEM. For analyzing the pinning effect, magnetization hysteresis of the samples were measured for H//c-axis in a Quantum Design SQUID magnetometer at various temperature from 10 K to 85 K. Critical current density J_c was calculated by the modified Bean's formula[11].

$$J_C = 20\Delta M \frac{1}{a}\left[\frac{1}{1-\frac{a}{3b}}\right]$$

where ΔM is the difference in magnetization between increasing and decreasing magnetic fields and a and b are sample dimension for a rectangular shape.

3. RESULTS AND DISCUSSION

Figure 1 shows a SEM photograph of the melt-textured (Sm/Y)1.8 crystal. It can be seen in Fig. 1 that the uniform (Sm/Y)211 inclusions are trapped within the (Sm/Y)123 matrix. The detailed microstructural analysis has been carried out by TEM on the same sample. TEM was performed on the sample annealed at 450 °C for 100 h.

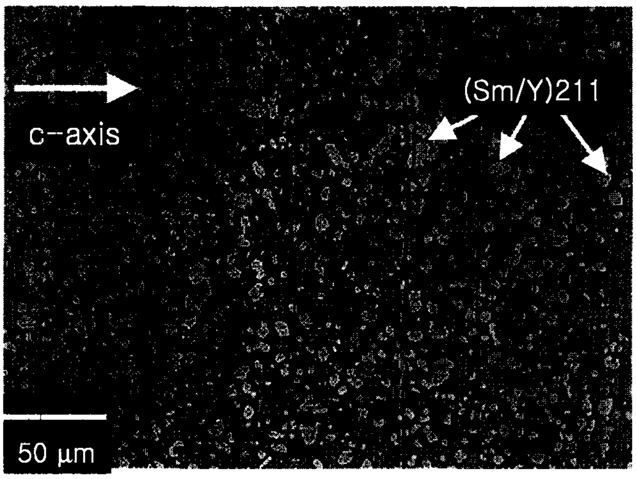

Fig. 1. SEM photograph of the melt-textured (Sm/Y)1.8 sample. Note finely dispersed (Sm/Y)211 inclusions are trapped into the (Sm/Y)123 matrix.

Fig. 2 shows TEM bright field image around the (Sm/Y)211 inclusion and selected area electron diffraction(SAED) pattern of the (Sm/Y)123 matrix viewed from a [001] direction. As shown in Fig. 2, (Sm/Y)123 matrix and (Sm/Y)211 inclusions are well crystallized, respectively. From the analysis of SEM and TEM data, only homogeneous (Sm/Y)123 and (Sm/Y)211 are observed, and impurity phase of Sm is not found.

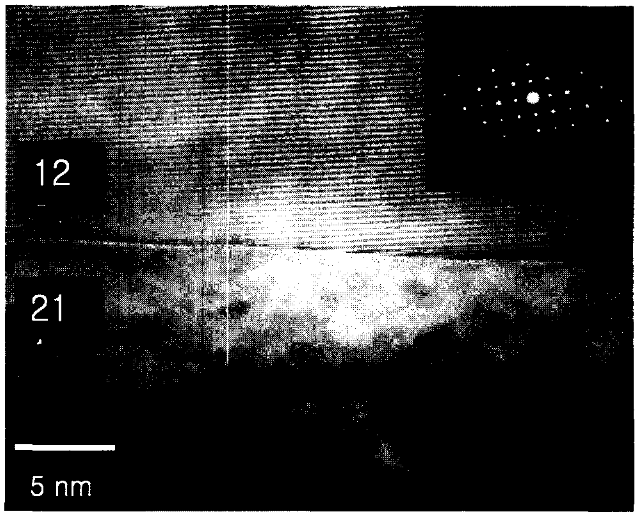

Fig. 2. High resolution TEM image and SAED pattern of the interface between a (Sm/Y)211 inclusion and (Sm/Y)123 matrix.

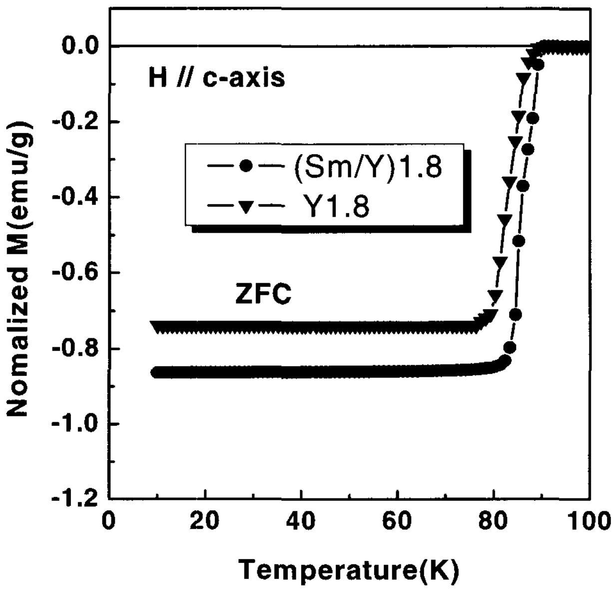

Fig. 3. Temperature dependence of magnetic susceptibility of the zone melt-textured (Sm/Y)1.8 and Y1.8 sample.

In order to find out how the sample consists of superco nducting phase, magnetic susceptibility of the zone melt-textured (Sm/Y)1.8 and Y1.8 samples were measured. The field of 10 Oe was applied parallel to the c-axis from 10 to 100 K. As shown in Fig. 3, the (Sm/Y) 1.8 sample shows a sharp superconducting transition at 9 1 K, indicating that the sample consists of a homogeneou s superconducting phase.

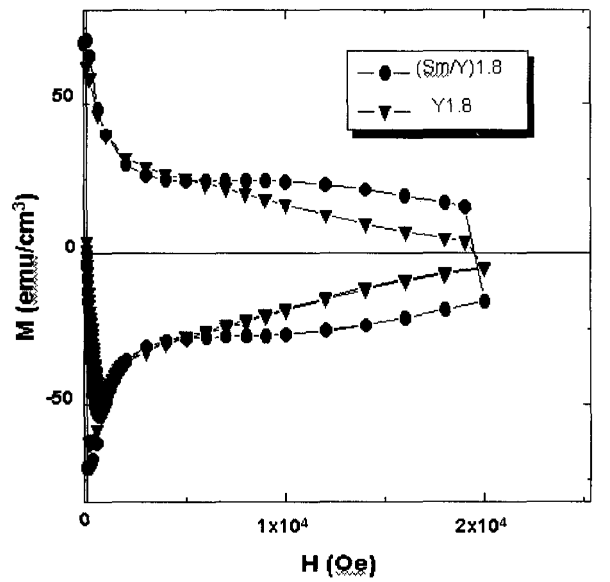

Fig. 4. Magnetization hysteresis loops of the zone melt-textured (Sm/Y)1.8 and Y1.8 sample.

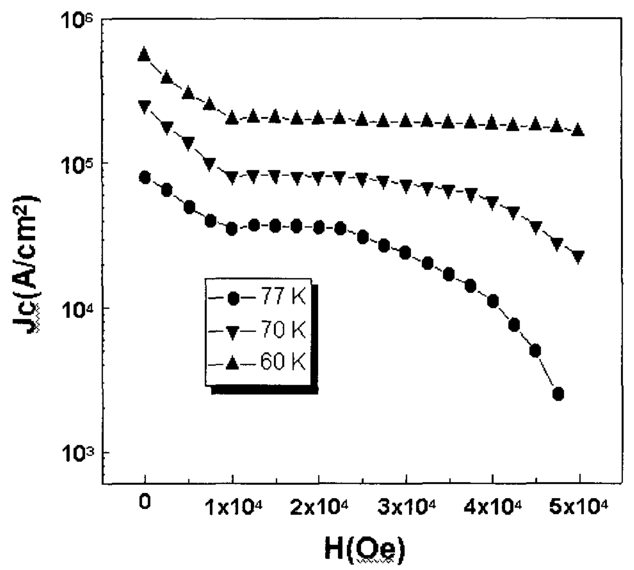

Fig. 5. Field dependence of critical current densities of the zone melt-textured (Sm/Y)1.8 sample at various temperatures.

For the analysis of flux pinning, magnetization hysteresis loops of (Sm/Y)1.8 and Y1.8 samples were measured from 10 to 85 K as a function of the magnetic field(//c-axis) up to 5 T. Among the hysteresis results, a representative hysteresis loop at 77 K is shown in Fig. 4. The (Sm/Y)1.8 sample shows about 2.5 times larger magnetization hysteresis loop than that of zone melt-textured Y1.8 sample at 2 tesla.

To increase pinning effect, total area of the interface should be important ; smaller Y211 inclusions are more efficient in enhancing flux pinning. It is reported that the melt-textured YBCO, fabricated by MPMG method, exhibits enormous magnetic hysteresis loop because Y211 inclusions in Y123 matrix work as pinning centers[5].

The SEM photograph of (Sm/Y)1.8 sample in Fig. 1 shows that (Sm/Y)211 inclusions of about 1~10 μm^2 are distributed in a large (Sm/Y)123 matrix. Fig. 2 exhibits that the interface between (Sm/Y)211 inclusion and (Sm/Y)123 matrix is sharp. The pinning effect in SmBCO (OCMG) is larger than that in YBCO, indicating that the superconducting (Sm/Y)123 phase in our (Sm/Y)1.8 sample may have enhanced pining effect as well[9,10]. The sharp interface as well as the substitution of Sm for the half of Y in (Sm/Y)1.8 compound may provide more effective pinning centers than in Y1.8 samples[5].

The critical current densities of the (Sm/Y)1.8 sample derived from the magnetization hysteresis loops at various temperatures are shown in Fig. 5. As illustrated in Fig. 5, the field dependence of critical current densities rapidly decreases with increasing of applied fields at 77 K, while it does not change that much at 60 K regions. The critical current density J_c of our sample is calculated at 1 T and 77 K. The value of J_c is 3.5×10^4 A/cm^2, which is higher than that of Y1.8 sample.

For a comparison of the pinning strength between different high T_c superconductors, a simultaneous location of their irreversibility lines in the field-temperature(H-T) has been useful. Irreversibility line defines a boundary in the H-T phase diagram above which J_c is immeasurably small or zero. Zero resistance state is only achieved in pinned or irreversible high T_c superconductors, in which flux motion is prevented by pinning centers against the electromagnetic force.

Since high T_c superconductors cannot be used beyond this line, it is desirable that the materials have high enough irreversibility field at a temperature where they are used. According to the collective flux creep theory[12], the irreversibility field H_{irr} is given by

$$H_{irr} \propto \left[1-\left(\frac{T}{T_C}\right)^m\right]^n$$

A fitting formula has been tried for various exponents m and n. This scaling behavior of $H_{irr} \propto [1-(T/T_c)^2]^{1.5}$for melt-textured YBCO superconductors was also reported[12]. Several techniques are used in determining the irreversibility field. In this paper, we have adopted t he DC magnetization method by SQUID magnetometer.

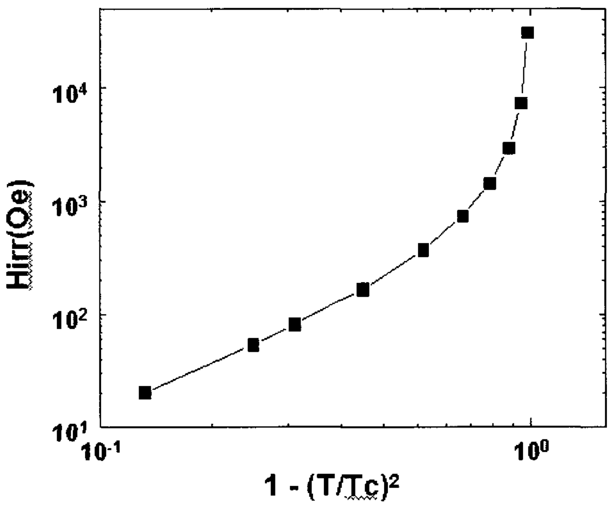

Fig. 6. Irreversibility field with reduced temperature of the zone melt-textured (Sm/Y)1.8 sample.

Figure 6 shows the irreversibility field(H_{irr}) versus reduced temperature $[1-(T/T_c)^2]$ on logarithmic scales for the (Sm/Y)1.8 sample. From least square fit of the data, $n \cong 1.6$ was calculated. This means that the temperature dependence of irreversibility line is close to YBCO(n=1.5), and the irreversibility fields(H_{irr}) show a drastic change in low temperature regions, while they reveal a slight change in high temperature regions.

4. CONCLUSION

In summary, we have succeeded in the syntheses of directionally melt-textured (Sm/Y)1.8 superconductor, where (Sm/Y)211 inclusions are uniformly dispersed within (Sm/Y)123 matrix by the zone melt growth process in air. The (Sm/Y)1.8 sample as a sharp transition temperature of 91 K consists of homogeneous superconducting phase. The sample shows a larger hysteresis loop than other Y1.8 melt-textured superconductors, indicating that flux pinning is effectively increased. The enhancement of flux pinning may be associated with the well-defined interface between (Sm/Y)211 and (Sm/Y)123 as well as the substitution of Sm for the half of Y site in (Sm/Y)1.8 compound. This result would be useful for the application fields of the high T_c bulk superconductors that require large critical current even at high magnetic field.

REFERENCES

[1] P. McGinn, W. Chen, N. Zhu, M. Lanagan, and U. Balanchandran, "Microstructure and critical current density of zone melt textured $YBa_2Cu_3O_{6+x}$", Appl. Phys. Lett., Vol. 57, No. 14, p. 1455, 1990.

[2] Donglu Shi, H. Krishnan, J. M. Hong, and D. Miller, "Transport critical current density and microstructure in extruded $YBa_2Cu_3O_{7-x}$ wires processed by zone melting", J. Appl. Phys., Vol. 68, No.1, p. 228, 1990.

[3] F. Giovannelli, S. Marinel, and I. Monot-Laffez, "Melt processing of (light rare earth)$Ba_2Cu_3O_y$ materials by the floating zone method", Supercond. Sci. Technol., Vol. 15, p. 533, 2002.

[4] P. McGinn, N. Zhu, W. Chen, S. Sengupta, and T. Li, "Microstructure and critical current density of zone melt textured $YBa_2Cu_3O_{6+x}$ with Y_2BaCuO_5 additions", Physica C, Vol. 176, p. 203, 1991.

[5] M. Murakami, S. Gotoh, H. Fujimoto, K. Yamaguchi, N. Koshizuka, and S. Tanaka, "Flux pinning and critical currents in melt processed YBaCuO superconductors", Supercond. Sci. Technol., Vol. 4, p. 43, 1991.

[6] S. I. Yoo, N. Sakai, T. Higuchi, and M. Murakami, "Melt processing for obtaining $NdBa_2Cu_3O_y$ superconductors with high T_c and large J_c", Appl. Phys. Lett., Vol. 65, No. 5, p. 633, 1994.

[7] S. I. Yoo, M. Murakami, N. Sakai, T. Higuchi, and S. Tanaka, "Enhanced T_c and Strong Flux Pinning in Melt-Processed $NdBa_2Cu_3O_y$ Superconductors", Jpn. J. Appl. Phys., Vol. 33, p. L1000, 1994.

[8] M. Murakami, S. I. Yoo, T. Higuchi, N. Sakai, M. Watanabiki, N. Koshizuka, and S. Tanaka, "A new type of pinning center in melt grown Nd123 and Sm123", Physica C, Vol. 235, p. 2781, 1994.

[9] S. J. Kim and H. G. Kim, "Effects of 211 inclusions on zone melt-textured (RE/Y)-Ba-Cu-O superconductors", Physica C, Vol. 338, p. 110, 2000.

[10] S. J. Kim, "Melt Textured Growth and Superconducting Properties of RE^{3+} Elements Doped YBCO Superconductors", J. of KIEEME(in Korea), Vol. 16, No. 3, p. 231, 2003.

[11] E. M. Gyory, R. B. van Dover, K. A. Jacson, L. F. Schneemeyer, and J. V. Waszczak, "Anisotropic critical currents in $Ba_2YCu_3O_7$ analyzed using an extended Bean model", Appl. Phys. Lett., Vol 55, No. 3, p. 283, 1989.
[12] N. Ihara and T. Matsushita, " Effect of flux creep on irreversibility lines in superconductors", Physica C, Vol. 257, p. 223, 1996.