Size Dependencies of the Peak Effect and Irreversibility Field in Superconducting Sm-123 Powders

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Abstract

Size dependencies of the peak effect and irreversibility field in superconducting Sm-123 powder specimens were investigated. The peak effect was found to disappear in the two-dimensional pinning regime in which powder size is smaller than pinning correlation length. This shows that the peak effect does not originate directly from elementary pinning mechanisms, but from a cooperative phenomenon of flux lines, as proposed by the pinning-induced disorder transition model. In addition, when powder size is smaller than virtual pinning correlation length in the ideal creep-free case, irreversibility field decreases with powder size. This supports the hypothesis that longitudinal flux bundle size is given by this length, as predicted by flux creep theory. These findings indicate that pinning correlation length is a general parameter that determines various properties associated with flux pinning phenomena.

Keywords: Sm-123, superconducting powder, peak effect, irreversibility field, pinning correlation length

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1 Introduction

It is well known that the irreversibility field of a superconductor depends on flux pinning strength[1] and electromagnetic anisotropy of the superconductor[2]. In addition, studies have clarified that the irreversibility field also depends on the size of superconducting specimens; specifically, Sawa *et al.*[3] found that as the thickness of Y-123 thin film decreases, vortex-glass liquid transition temperature, which is closely related to irreversibility temperature, decreases in a magnetic field along the direction of thickness. This suggests that irreversibility field decreases with decreasing film thickness. In addition, the irreversibility field was found to be much lower than that of thick tape, even for a more anisotropic Bi-2223 superconductor[1]. Hence, such size dependence of the irreversibility field seems to be a general phenomenon independent of anisotropy.

This behavior can be explained by collective flux creep theory[1, 4], which states that effects of thermal activation of flux lines are more significant in thinner films, because the pinning potential is limited by film thickness. In this case, the critical thickness differentiating a thin film from a bulk specimen is the pinning correlation length:

$$L = \left(\frac{C_{44}}{\alpha_{\mathrm{L}}}\right)^{1/2} \simeq \left(\frac{Ba_{\mathrm{f}}}{2\pi\mu_0 J_{\mathrm{c0}}}\right)^{1/2}, \tag{1}$$

where $C_{44} = B^2/\mu_0$ is the local tilt modulus of flux lines, α_{L} is the Labusch parameter, a_{f} is flux line spacing, and J_{c0} is the virtual critical current density in the flux creep-free case. Pinning potential in thin film and bulk specimen cases are given by [1]

$$U_0 = \frac{1}{2}\alpha_{\mathrm{L}} d_{\mathrm{i}}^2 \cdot d(a_{\mathrm{f}} g)^2; \quad d < L,$$

$$= \frac{1}{2}\alpha_{\rm L} d_{\rm i}^2 \cdot L(a_{\rm f} g)^2; \quad d > L, \tag{2}$$

where $d_{\rm i} = a_{\rm f}/2\pi$ is the interaction distance of weak point pins in the collective pinning regime[5] and $a_{\rm f}g$ is the transverse flux bundle size, with g^2 denoting the number of flux lines in the flux bundle. Since g^2 proportional to the shear modulus, C_{66}, depends on thermally activated flux lines, it can not be determined analytically. Hence, it is assumed that the value of g^2 that minimizes the energy dissipation under the flux creep is preferred[6]. Using the relationships $\alpha_{\rm L} d_{\rm i} = J_{\rm c0} B$ and $B = 2\phi_0/\sqrt{3}a_{\rm f}^2$, where ϕ_0 denotes a flux quantum, Eq. (2) is written as

$$\begin{aligned} U_0 &= \frac{4.23 g^2 k_{\rm B} J_{\rm c0} d}{2\pi B^{1/2}}; \; d < L, \\ &= \frac{0.835 g^2 k_{\rm B} J_{\rm c0}^{1/2}}{(2\pi)^{3/2} B^{1/4}}; d > L, \end{aligned} \tag{3}$$

where SI unit relationships: $(1/2)(2/\sqrt{3})^{3/2}\phi_0^{3/2} \simeq 4.23 k_{\rm B}$ and $(1/2)(2/\sqrt{3})^{7/4}(\phi_0^7/\mu_0^2)^{1/4} \simeq 0.835 k_{\rm B}$ are used. The effects of flux pinning strength and superconductor anisotropy are derived from $J_{\rm c0}$ and g^2, respectively[1, 7].

Usually critical current density, $J_{\rm c}$, takes a value smaller than $J_{\rm c0}$ by virtue of flux creep. The corresponding pinning correlation length,

$$l_{44} \simeq \left(\frac{B a_{\rm f}}{2\pi \mu_0 J_{\rm c}} \right)^{1/2}, \tag{4}$$

is approximately the same as Campbell's AC penetration depth[8]: $l_{11} = (C_{11}/C_{44})^{1/2} l_{44}$, where C_{11} denotes the uniaxial compression modulus of flux lines. If the superconductor is smaller than this length, the pinning mechanism is of a lower dimension[7]. This suggests that the peak effect, which is thought to be caused by a pinning-induced order-disorder transition[10], may also be influenced by the size of the superconductor. In fact, Takahama *et* *al.*[11] found that the peak effect tends to disappear as Sm-123 powder specimens are reduced in size. The question of whether correlation length, which determines the irreversibility field, is also a critical dimension for the peak effect remains.

The present study seeks to answer this question, by investigating the peak effect and irreversibility field in Sm-123 powder specimens of various particle sizes.

2 Experimental

Sm-123 powder specimens were prepared by liquid-phase sintering technique, from the correct ratios of powders of Sm_2O_3, $BaCO_3$, and CuO. The powder mixture was calcined in air at 900 °C for 24 h. After being reground, the powder was pressed into pellets and sintered again at 950 °C for 40 h in 0.1 % O_2-Ar gas. Finally, the pellets were post-annealed at 350 °C for 40 h in flowing O_2 gas, and crushed into powder. Powders of different particle sizes were classified by means of a sieve and sedimentation (elutriation) method. Details of this method are described in[11]. Table 1 lists average particle size and standard deviation for five specimens. These powder specimens were mixed with Y_2O_3 particles at a weight ratio of 1 to 6, in order to prevent a shielding current from flowing between grains. Then, the powder specimens were pressed uniaxially, with c-axes of the particles being aligned along the pressed direction. This was ascertained by measuring the peak effect. The specimens had critical temperatures falling within the range of 93.2 to 93.8 K.

A SQUID magnetometer was used to measure DC magnetization of the specimens in a magnetic field parallel to the c-axis. The slope of the minor magnetization curve at a point where the sweep of the external magnetic field changed from increasing to decreasing was also measured to examine surface pinning effects. Using Bean's model for spherical geometry, critical current density, J_c, was estimated from observed magnetization hysteresis. The irreversibility field, B_i, was determined as the magnetic field at which J_c dropped to 1.0×10^7 A/m^2.

Figure 1 shows the critical current density of five specimens at 77.3 K. The peak effect is most pronounced in specimen 1, which has the largest particle size. As average particle size, $\langle d \rangle$, decreases, the peak effect becomes less pronounced and finally disappears. Additionally, the results show that as $\langle d \rangle$ decreases, J_c at low fields tends to increase and B_i tends to decrease. When a magnetic field was applied perpendicular to the direction of uniaxial pressing, the peak effect could not be detected, even in specimen 1. This shows that the c-axes are approximately aligned along the direction of uniaxial pressing.

Figures 2(a) and 2(b) show the critical current densities of specimens 1 and 3 at various temperatures and magnetic fields. In the case of specimen 1, the peak effect is observed over almost the entire measured temperature range. This behavior is similar to that of large single crystals or bulk specimens. In specimen 3, the J_c-B curve at 77.3 K shows a plateau, while curves at lower temperatures show pronounced peaks, and curves at higher temperatures show rapid, monotonous decrease. The peak effect was not observed in specimens 4 and 5, even when the temperature was lowered to 70 K. The difference in behavior between specimen 1 and the other specimens seems to be caused by size effects.

Figure 3 shows the slope, S, of the minor magnetization curve of specimens 1 and 3 at 77.3 K. The value of large specimen 1 is close to 3/2 showing that the spherical model is suitable for the present powder specimens. On the other hand, the slope of specimen 3 takes a much smaller value and decreases monotonically with increasing field. Such low values of slope at high fields shows that flux lines go out the specimen almost freely when the sweep changes from increasing to decreasing. The same thing happens when the external magnetic field is increased again after a sufficient decrease. Thus, it can be concluded that strong surface pinning does not manifest in the present specimens.

Figure 4 shows the temperature dependence of irreversibility field for each specimen. Figure 5 shows the particle size dependence of irreversibility field at 77.3 K; irreversibility field tends to increase with particle size, up to a saturation point. This agrees qualitatively with the behavior predicted by the flux creep theory[1]. Since irreversibility field depends not only on particle size, but also on pinning strength, which itself varies with particle size, determining the pure size dependence of irreversibility field requires theoretical analysis, which is presented in the next section.

3 Discussion

As shown in Fig. 1, critical current density at low fields, which is not strongly affected by flux creep, depends on particle size. That is, J_c tends to be larger in a specimen of smaller particle size. This can be explained by the concept of collective flux pinning. In the regime of two-dimensional pinning, in which particle size, d, is smaller than l_{44}, J_c has been predicted to be proportional to $d^{-1/2}$[9], even if the size and number density of pinning centers remain unchanged. Such size dependence has been demonstrated in Y-123 thin films[12]. In the three-dimensional pinning regime of $d > l_{44}$, J_c is independent of size.

Surface pinning also gives rise to size dependence of J_c. That is, J_c is expected to be proportional to d^{-1} in the limit of small specimens, while J_c is independent of d for large specimens. However, it is shown here that surface pinning does not work.

Such decreases in S are known to be associated with the reversible motion of flux lines in pinning potentials. This motion is prominent when specimen size is comparable to or smaller than pinning correlation length l_{44}, and S is proportional to $(d/l_{44})^2$ for $d \ll l_{44}$[13]. The decrease in S is caused by the increase in l_{44} due to a decrease in J_c.

Thus, the dimension of flux pinning plays a dominant role in pinning properties of the present specimens. Hence, occurrence of the peak effect shown in Figs. 1 and 2 also seems to be influenced by the dimension of flux pinning, as determined by the size of specimen relative to l_{44}. Figure 6 shows $\langle d \rangle / l_{44}$ for each specimen at 77.3 K, and suggests that the peak effect disappears when $\langle d \rangle$ is smaller than $l_{44}/2$ in the field region in which disorder transitions take place in bulk specimens. Figure 7(a) shows the magnetic field dependence of $\langle d \rangle / l_{44}$ in specimen 3 at various temperatures; the same behavior is found as in Fig. 6. Figure 7(b) shows the same variations in specimen 1; at each temperature, $\langle d \rangle$ is larger than $l_{44}/2$ throughout almost the entire field region, suggesting that the pinning mechanism is three-dimensional, which is usually observed in bulk specimens. Disappearance of a clear peak effect at high temperature is thought to be caused by flux creep. Thus, the peak effect disappears in the two-dimensional pinning regime for less anisotropic or three-dimensional Sm-123 superconductors.

It was confirmed that l_{44} directly observed by Campbell's method agrees well with Eq. (4) using observed J_c values for Bi-2212 single crystal[14] and for bulk Y-123[7]. This means that $l_{44}/2$, as argued above, is an exact threshold value of size.

The collective pinning mechanism predicts that, for specimens smaller than $l_{44}/2$, flux lines easily arrange by themselves to fit randomly dispersed pinning centers, by virtue of less significant interference of pinning interactions along their length, thereby resulting in larger values of J_c. Thus, additional deformation of flux lines seems to be difficult even at field strengths where softening starts due to disorder transition. That is, the gain in pinning energy of flux lines is already large, and the further gain realized when flux lines deform slightly further is not large. This explains the disappearance of the peak effect in small specimens. We should note here that the corresponding deformation is shear, as argued [10]. This is different from the case of the most anisotropic Bi-2212 superconductor, in which the deformation responsible for the peak effect is bending, which results from crossover from three-dimensional state to two-dimensional state[15].

The disappearance of the peak effect in small specimens could be ascribed to a transition from bulk pinning, which causes the peak effect, to surface pinning. However, there is no contribution from surface pinning. Hence, it can be concluded that this disappearance is not such a transition. The fact that the peak effect disappears at high temperatures as shown in Fig. 2(b) supports this conclusion.

A field-induced pinning mechanism was proposed to explain the peak effect in 123 superconductors[16]. This might explain the disappearance of the peak effect at the high temperatures shown in Fig. 2(b). However, the appearance of the peak effect in specimen 1 at temperatures up to T_c is incompatible with this explanation for specimen 3. In addition, the disappearance of the peak effect in sufficiently small specimens shows clearly that the peak effect is not caused by field-induced pinning mechanisms. This is consistent with experimental findings that the peak effect in Y-123[17] and Nd-123[18] deteriorates with the addition of 211 and 422 phase particles, respectively. This is thought to be caused by interference between attractive condensation energy interactions of non-superconducting particles, and pinning interactions of defects responsible for the peak effect, such as oxygen deficient regions and regions where Ba sites are substitutionally occupied by RE elements. The elementary pinning mechanism in such low $T_{\rm c}$ regions is thought to be the kinetic energy interaction with a repulsive force[17], which decreases monotonically with increasing magnetic field.

The above argument shows that the peak effect observed in powder specimens originates from the order-disorder transition of flux lines, and its disappearance in small specimens is caused by the crossover from three-dimensional pinning to two-dimensional pinning. In addition, the fact that the crossover of flux pinning influences order-disorder transition shows that disorder in the flux line lattice is induced by pinning interactions[10], rather than by thermal agitation as assumed in [19].

Specimen size dependence of the irreversibility field can be evaluated roughly using Eq. (3) and flux creep theory[1, 4]. If we assume uniform values of flux pinning strength and particle size, neglecting their wide distributions, we can derive a simple relationship. Since the activation barrier reaches pinning potential in the irreversibility field where current density J goes to zero, a condition for the irreversibility field, as given by [4], is

$$E_{\rm c} = B a_{\rm f} \nu_0 \exp\left(-\frac{U_0(B_{\rm i})}{k_{\rm B}T} \right), \tag{5}$$

where E_c is the electric field criterion for determining J_c, a_f is approximate hopping distance, ν_0 is an attempt frequency, and $U_0(B_\mathrm{i})$ is the pinning potential at the irreversibility field. If the dependence of $J_{\mathrm{c}0}$ on B and T is given by

$$J_{\mathrm{c}0}(B,T) = A\left[1-\left(\frac{T}{T_\mathrm{c}}\right)^2\right]^m B^{\gamma-1}; \qquad B \ll B_{\mathrm{c}2}, \tag{6}$$

Eqs. (3) and (5) lead to

$$\begin{aligned}\left(\frac{B_\mathrm{i}}{B_\mathrm{imax}}\right)^{(3-2\gamma)/2} &= \frac{d}{L}; d < L, \\ &= 1;\ d > L,\end{aligned} \tag{7}$$

where B_imax is the irreversibility field in the bulk limit[4]:

$$B_\mathrm{imax}^{(3-2\gamma)/2} = \left(\frac{K}{T}\right)^2\left[1-\left(\frac{T}{T_\mathrm{c}}\right)^2\right]^m; \qquad K = \frac{0.835 g^2 A^{1/2}}{(2\pi)^{3/2}\log(B a_\mathrm{f}\nu_0/E_\mathrm{c})}. \tag{8}$$

This shows that irreversibility field increases with size according to a power law, and when size exceeds correlation length, the irreversibility field saturates to a bulk value.

In reality the phenomenon is more complicated, because of the distribution of flux pinning strength and other factors. Precise estimation of the irreversibility field of a specimen requires numerical calculation using the flux creep-flow model[20]. For simplicity, we assume that A, which represents the strength of flux pinning, is the only variable that exhibits a distribution, since its distribution is much wider than that of powder size[21]. The distribution function of A is assumed to be

$$f(A) = G\exp\left[-\frac{(\log A - \log A_\mathrm{m})^2}{2\sigma^2}\right], \tag{9}$$

where A_m is the most probable value of A, σ^2 is a parameter representing distribution width, and G is a constant. Table 2 lists the parameters A_m,

σ^2, m, γ, and g^2 used in the calculation of E-J characteristics. Theoretical value of J_c was obtained around $E \simeq 10^{-9}$ V/m typical for the present DC magnetization measurement. These parameters were adjusted such that the theoretical $J_\mathrm{c}(B,T)$'s agree with experimental results, except for the peak region. The number g^2 is slightly larger than theoretically predicted values of similar Y-123 superconductors[7]. A larger particle provides a larger contribution to magnetization and has a higher irreversibility field. Hence, the observed irreversibility field is determined mostly by large particles rather than by particles of average size. Relatively large g^2 values found in small specimens are an artifact of the use of average powder size in analysis.

The irreversibility field was theoretically determined according to the same criterion used in the experiment. Figure 8 shows the relationship between normalized irreversibility field and normalized particle size at 77.3 K. The theory is found to explain the experimental results well. A low irreversibility field is ascribed to the pinning potential of flux bundles being smaller due to volume being limited by specimen size. The good agreement shown in Fig. 8 demonstrates that the bulk longitudinal flux bundle size is correctly given by Eq. (1).

Thus, the expression for pinning potential given in Eq. (3) is a good general description of the flux creep phenomenon with respect to dependencies on flux pinning strength, anisotropy of the superconductor, and specimen size.

In the present study, pinning correlation length is found to play an important role in the pinning properties of less anisotropic superconductors such as Sm-123; it determines the dimensionality of pinning. In the two-dimensional pinning regime where specimen size is smaller than this correlation length, critical current density is higher, the peak effect disappears, and irreversibility field is lower than in the bulk case. In addition, in a superconductor that is smaller than correlation length, electromagnetic phenomena also differ completely from predictions of the irreversible critical state model. For instance, the value of AC loss is much smaller than the theoretically predicted value[13], and AC response characteristics, such as susceptibility, behave differently to predictions[22]. Such peculiar behaviors originate from the reversible motion of flux lines inside the pinning potential[8].

Thus, we can conclude that pinning correlation length is a general parameter that determines pinning properties and related phenomena.

4 Summary

Size dependencies of the peak effect and irreversibility field were investigated in superconducting Sm-123 powder specimens of different average particle sizes. The following results were found.

(1) The peak effect disappears in the two-dimensional pinning regime when powder size is smaller than pinning correlation length. This shows that the peak effect originates from the pinning-induced order-disorder transition of flux lines rather than from elementary field-induced pinning mechanisms.

(2) The irreversibility field decreases as powder size becomes smaller than from the virtual pinning correlation length in the creep-free case, which is the longitudinal flux bundle size. This is caused by the reduction in pinning potential as explained by flux creep theory.

(3) Since pinning correlation length determines not only pinning properties, but also electromagnetic properties such as AC losses, this correlation length is

found to be an important parameter that determines various general properties associated with flux pinning phenomena.

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Table 1. Sm-123 powder specimen data.

Table 2. Pinning parameters of Sm-123 powder specimens.

Fig. 1. Magnetic field dependence of critical current density of five powder specimens at 77.3 K.

Fig. 2. Critical current density of (a) specimen 1 and (b) specimen 3 at various temperatures.

Fig. 3. Slope of minor magnetization curve of specimens 1 and 3 at 77.3 K when external magnetic field sweep changes from increasing to decreasing, as shown in the inset.

Fig. 4. Temperature dependence of irreversibility field.

Fig. 5. Particle size dependence of irreversibility field at 77.3 K.

Fig. 6. Magnetic field dependence of $\langle d \rangle / l_{44}$ of each specimen at 77.3 K.

Fig. 7. Magnetic field dependence of $\langle d \rangle / l_{44}$ of (a) specimen 3 and (b) specimen 1 at various temperatures.

Fig. 8. Relationship between normalized irreversibility field and normalized particle size at 77.3 K. Symbols show experimental results, while lines show corresponding theoretical predictions.

Table 1. Sm-123 powder specimen data.

specimen	1	2	3	4	5
average size $\langle d \rangle$ (μm)	49.8	8.5	5.0	4.4	2.2
stand. dev. σ (μm)	15.4	4.5	2.9	3.0	1.3
T_c (K)	93.2	93.3	93.3	93.8	93.6

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Table 2. Pinning parameters of Sm-123 powder specimens.

specimen	1	2	3	4	5
$A_{\rm m}$	3.5×10^9	1.41×10^{10}	1.89×10^{10}	8.23×10^9	1.23×10^{10}
σ^2	0.005	0.07	0.10	0.15	0.15
m	2.5	1.6	1.5	1.5	1.5
γ	0.60	0.50	0.50	0.20	0.20
g^2	7.0	9.0	9.0	8.0	8.0