# FLUX PINNING CHARACTERISTICS IN $YBa_2Cu_3O_7$ WITH COLUMNAR DEFECTS

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## ABSTRACT

It was shown that columnar defects nucleated in high temperature superconductors by heavy ion irradiation work as strong pinning centers and enhance the irreversibility field in the high temperature region. In this study, the characteristics are theoretically investigated for $YBa_2Cu_3O_7$ in the magnetic field parallel to both the columnar defects and the $c$-axis. The normal core interaction of the columnar defects is assumed for the elementary pinning force and the statistical summation of those forces is carried out for the estimation of the virtual pinning force density in the creep-free case. The critical current density under the flux creep and the irreversibility field are numerically calculated using the flux creep theory. The obtained irreversibility field agrees well with the experimental results on an $YBa_2Cu_3O_7$ single crystal. Discussion is given on the pinning efficiency by randomly distributed columnar defects.

**KEYWORDS:** columnar defect, heavy ion irradiation, $YBa_2Cu_3O_7$ single crystal, critical current density, pinning force density, irreversibility field

## INTRODUCTION

It is known that the critical current density in high-$T_c$ superconductors decreases appreciably with increasing magnetic field and/or temperature in the high temperature region. These critical current characteristics are caused by the flux creep. However, the poor critical current characteristics are not completely owing to the intrinsic property of the superconductor, but the characteristics can be improved by introduction of strong pinning centers to some extent. Hence, it is desired to introduce pinning centers sufficiently strong to make their application at high temperatures possible. On the one hand, the critical current density of $YBa_2Cu_3O_7$ in which columnar defects are introduced by heavy ion irradiation takes a very high value in high magnetic fields and high temperatures and the irreversibility field is shifted to a higher temperature [1]. Although it is necessary to understand exactly the flux pinning characteristics by columnar defects for improvement of the characteristics in the future, it has not yet been analyzed theoretically. In this paper, therefore, the pinning force density in $YBa_2Cu_3O_7$ with the columnar defects is estimated using the statistical summation theory and the flux creep theory and the results is compared with the experiments by Civale *et al.* [1] on a single crystal.

## THEORY

It is assumed that the magnetic field is applied along the $c$-axis parallel to columnar defects with the length $L$ and the radius $R$. The radius $R$ is assumed to be larger than the coherence length, $\xi_\perp$, in the $a$-$b$ plane. The elementary pinning force of this columnar defect interacting with the fluxoid is estimated from the core pinning mechanism as

$$f_p \simeq \frac{\pi}{4\mu_0} B_c^2 \xi_\perp L, \tag{1}$$

where $B_c$ is the thermodynamic critical field. The number density of the columnar defects, $N_p$, is expressed as $B_\phi/\phi_0 W$, where $B_\phi$ is an equivalent magnetic field at which the fluxoid density is

equal to the defect density and $W$ is the thickness of the superconductor. Then, we shall define the effective pin density, $N'_{\rm p}$, which represents the number density of pinning interaction. This is given by the product of $N_{\rm p}$ and the probability for a defect to meet the fluxoid, $B\pi R^2/\phi_0$. Thus, we have

$$N'_{\rm p} = \frac{\pi R^2 B B_\phi}{W\phi_0^2}. \tag{2}$$

The virtual flux pinning force density is expressed as

$$F_{\rm p0} = J_{\rm c0}B = \eta N'_{\rm p} f_{\rm p} \tag{3}$$

in terms of the pinning efficiency, $\eta$. In the following the pinning efficiency is estimated by the statistical summation.

The whole fluxoid system is regarded as an ensemble of the parts the fluxoid lattice in each of which a short range order exists and one pinning interaction is contained. That is, the volume of each element is $1/N'_{\rm p}$. In each element the fluxoid lattice is interacting with a pinning center and suffers a local distortion around the pinning center. This distortion in the short range can be characterized by the elastic compliance of the fluxoid lattice against the line force parallel to the fluxoids. This is given as

$$G'(0) \simeq \frac{1}{4\pi L}\left[\frac{1}{2C_{11}}\log\left(\frac{4\pi BC_{11}}{\alpha_{\rm L}\phi_0}+1\right)+\frac{1}{2C_{66}}\log\left(\frac{4\pi BC_{66}}{\alpha_{\rm L}\phi_0}+1\right)\right], \tag{4}$$

where $C_{11}$ and $C_{66}$ are the uniaxial compression and shear moduli of the fluxoid lattice, respectively, and $\alpha_{\rm L}$ is the Labusch parameter. Usually $C_{11}$ is much larger than $C_{66}$, and in the case of strong pinning $\alpha_{\rm L}\phi_0/4\pi B$ is expected to be sufficiently larger than $C_{66}$. Thus, Eq. (4) is reduced to

$$G'(0) \simeq \frac{B}{2\alpha_{\rm L}\phi_0 L} \equiv k_{\rm f}^{-1}, \tag{5}$$

where $k_{\rm f}$ means the spring constant. On the one hand, it is considered that these elements are interacting with each other through the elasticity of the fluxoid lattice. This elastic interaction is expressed using the spring constant given by

$$K \simeq \alpha_{\rm L} a_{\rm f} L \lambda'_0, \tag{6}$$

where $a_{\rm f}$ is the fluxoid spacing and $\lambda'_0$ is Campbell's AC penetration depth. Since the distortion is linearly additive [2], the compliance of fluxoid is also additive and we have

$$k'^{-1}_{\rm f} = k_{\rm f}^{-1} + K^{-1}. \tag{7}$$

Since $k_{\rm f}/K \simeq a_{\rm f}/\lambda'_0 \ll 1$, $k'_{\rm f} \simeq k_{\rm f}$ is obtained.

If we use Campbell's statistical summation theory [3], the pinning force density is given by

$$F_{\rm p0} = N'_{\rm p} f_{\rm p} \frac{f_{\rm p} - f_{\rm pt}}{f_{\rm p} + f_{\rm pt}}, \tag{8}$$

where $f_{\rm pt} = k_{\rm f} a_{\rm f}/4$ is the threshold value for $f_{\rm p}$. The pinning force density is also expressed as $F_{\rm p0} = \alpha_{\rm L} d_{\rm i}$, where $d_{\rm i}$ denotes the interaction distance and is theoretically predicted as $d_{\rm i} = a_{\rm f}/2\pi$ [4]. Hence, a self-consistent solution can be obtained for $f_{\rm pt}$:

$$\frac{f_{\rm pt}}{f_{\rm p}} = \frac{-(s+1)+\sqrt{s^2+6s+1}}{2s} < 1, \tag{9}$$

where $s = \phi_0/\pi^2 R^2 B_\phi$. It can be shown that $f_{\rm pt}$ is a function of $f_{\rm p}$ and does not exceed $f_{\rm p}$. Hence, $F_{\rm p0}$ has always a nonzero value. From Eqs. (3) and (8) the pinning efficiency is expressed as

$$\eta = \frac{1 - f_{\rm pt}/f_{\rm p}}{1 + f_{\rm pt}/f_{\rm p}}. \tag{10}$$

The practical pinning force density is seriously affected by flux creep. According to the flux creep theory [5], the most important parameter to describe the flux creep is the pinning potential which is given by

$$U_0 = \frac{0.835 g^2 k_{\rm B} J_{\rm c0}^{1/2}}{2\pi^{3/2} B^{1/4}} \tag{11}$$

for a bulk superconductor. In the above $g^2$ is a number of fluxoids in the flux bundle and $J_{\rm c0} = F_{\rm p0}/B$ is the virtual critical current density in the creep-free case. Here, the magnetic field and temperature dependences of $J_{\rm c0}$ are assumed to be expressed as

$$J_{\rm c0} = A B_{\rm c2}^m(0) \left[1 - \left(\frac{T}{T_{\rm c}}\right)^2\right]^m B^{\gamma-1} \left(1 - \frac{B}{B_{\rm c2}}\right)^\delta, \tag{12}$$

where $AB_{\rm c2}^m(0)$, $m$, $\gamma$ and $\delta$ are the pinning parameters. Then, the $E$-$J$ characteristics can be calculated numerically by using the flux creep model [6]. For theoretically obtained $E$-$J$ curves, the critical current density is determined by the off-set method at the electric field of $1.0 \times 10^{-5}$ V/m. Further details of the numerical calculation are given in Ref. [7].

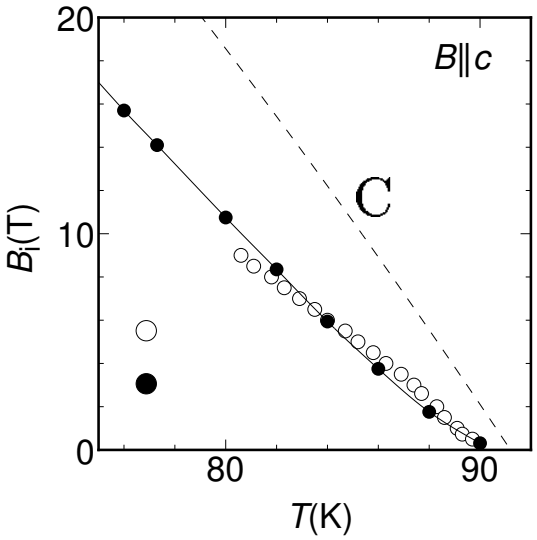
## RESULTS AND DISCUSSION

We shall discuss the case of $B_\phi = 5.0$ T. The size of the columnar defects irradiated by Sn ions is $R = 2.5$ nm and $L \simeq W = 20$ $\mu$m [1]. The assumed superconducting parameters are $B_{\rm c2\parallel}(0) = 80.5$ T, $B_{\rm c\parallel}(0) = 1.0$ T, $T_{\rm c} = 91.2$ K and $\xi_\perp(0) = 2.02$ nm. In this case we estimate as $f_{\rm pt}/f_{\rm p} = 0.12$ and we have $\eta = 0.79$. Hence, the virtual pinning force density at 0 K and 1 T is $2.28 \times 10^{10}$ A/m$^2$. The superconducting and pinning parameters used for the calculation are shown in Table 1.

In the beginning, the experimental results of irreversibility field [1] are compared with the present theoretical results. Figure 1 shows the theoretically obtained irreversibility field defined as the magnetic field at which the critical current density is reduced to $1.0 \times 10^5$A/m$^2$ in the field. The agreement is satisfactory and it can be said that the pinning characteristics of the columnar defects nucleated by heavy ion irradiation are well explained the statistical summation theory of pinning forces and the flux creep theory. The virtual pinning force density, $F_{\rm p0}$, and the theoretically obtained pinning force density, $F_{\rm p}$, are compared with the experimental result at 77 K in Fig 2. It is found that the magnetic field dependence of $F_{\rm p}$ is slightly different between the theoretical and experimental results. This difference is considered to be partly caused by the overestimation of the irreversibility field. This overestimation is due to the extrapolation use of $g^2 = 2.3$ estimated at 80 K and 9.5 T to the lower temperature region. Although the agreement

Table 1. Superconducting and pinning parameters in $YBa_2Cu_3O_7$ single crystal used for calculation.

| $T_{\rm c}$ (K) | $B_{\rm c2\parallel}(0)$ (T) | $B_{\rm c\parallel}(0)$ (T) | $\rho_{\rm n}(T_{\rm c})$ ($\mu\Omega$m) | $\xi_\perp(0)$ (nm) | $AB_{\rm c2}^m(0)$ | $m$ | $\gamma$ | $\delta$ | $\zeta$ |
|---|---|---|---|---|---|---|---|---|---|
| 91.2 | 80.5 | 1.0 | 2.0 | 2.02 | $2.28 \times 10^{10}$ | 1.5 | 0.5 | 2.0 | $2\pi$ |


20
10
0
80
90
$B_i$(T)
$T$(K)
$B \| c$
C