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INFLUENCE OF PINNING CENTER DISTRIBUTION ON THE PINNING OF TWO-DIMENSIONAL VORTEX SYSTEM*

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Abstract: The superconductor sample had periodic distribution of pinned region (with length of L_p) and unpinned region (with length of $L - L_p$) along the driving force direction. Numerical study on the influence of the distribution of pinning centers on pinning of the two-dimensional vortex system showed that the critical depinning force F_c, beyond which the vortex system begins to depin, increases with increase of L_p, indicating that the homogeneity of pinning centers helps to enhance the critical electric current of a superconductor. We found that the critical depinning force F_c depends logarithmically on L/L_p.

Key words: superconductor, vortex lattice, pinning, critical force
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INTRODUCTION

The physics of a vortex lattice (VL) in type-II superconductors has been the focus of interest since the beginning of high-T_c research. It is well-known that, after the external magnetic field exceeds its critical value H_{c1}, the magnetic field can penetrate a type-II superconductor in the form of Abrikosov vortices each carrying a quantum of magnetic flux $\Phi_0 = h/2e$.

In particular, the pinning of VL by material defects in a superconductor has recently been the subject of intense investigations because the pinning of VL can immobilize vortices, reduce dissipation effects, and create high critical currents (Blatter et al., 1994). A two-dimensional (2D) vortex system can approximately describe the VL in superconductor thin films and multilayers, especially those irradiated by heavy energy ions (Troyanovski et al., 1999). At zero temperature these systems exhibit a sharp depinning transition from a pinned state below a critical driving force F_c to a sliding state above F_c, the critical force which relates to the critical electric current density J_c of real superconductors. It was demonstrated that F_c and J_c are affected by many factors, such as pinning strength, pinning center density, temperature, field, and pinning center distribution (Higgins et al., 1996; Koshelev, 1992; Cao et al., 1999; Jensen et al., 1996).

In this work, numerical simulation was carried out to determine the influence of pinning center distribution on the pinning of a 2D vortex system. In a real superconductor, the distribution of pinning centers is usually inhomogeneous. Our simulation focused on a simple case: pinned region (PR) and unpinned region (UR) arrayed periodically in the direction of the driving force, and also investigated the dependence of the critical depinning force on the pinning center distribution by changing the size of the PR while keeping the number of pinning centers and vortices constant. In our simulations, the Magnus force caused by vortex motion and quantum fluctuation were not considered.

MODEL

We employ overdamped molecular dynamic

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(MD) simulation at zero temperature to study 2D interacting vortices in the presence of point-like pinnings (Reichhardt et al., 1996, 1997),

$$\eta \frac{d\boldsymbol{r}_i}{dt} = \sum_{j\neq i}^{N_v} \boldsymbol{F}_{vv}(\boldsymbol{r}_i - \boldsymbol{r}_j) + \sum_{k=1}^{N_p} \boldsymbol{F}_{pv}(\boldsymbol{r}_i - \boldsymbol{R}_k) + \boldsymbol{F}. \quad (1)$$

Here η is the viscosity coefficient, $\{\boldsymbol{R}_k\}$ specifies the N_p pinning center positions, $\boldsymbol{r}_i$ denotes the location of the ith vortex, and $\boldsymbol{F}$ is the driving force. The parameter η is fixed at unity. The force between vortices is given by

$$\boldsymbol{F}_{vv}(\boldsymbol{r}_i - \boldsymbol{r}_j) = f_0 K_1(|\boldsymbol{r}_i - \boldsymbol{r}_j|/\lambda)\hat{\boldsymbol{r}}_{ij}, \quad (2)$$

where $K_1(r/\lambda)$ is a modified Bessel function, λ is the penetration depth, and $\hat{\boldsymbol{r}}_{ij} = (\boldsymbol{r}_i - \boldsymbol{r}_j)/|\boldsymbol{r}_i - \boldsymbol{r}_j|$. A cutoff is placed on $K_1(r/\lambda)$ after it reaches an extremely small value at $r = 6\lambda$. The pinning force is taken as

$$\boldsymbol{F}_{pv}(\boldsymbol{r}_i - \boldsymbol{R}_k) = (f_p/r_p)|\boldsymbol{r}_i - \boldsymbol{R}_k|\Theta((r_p - |\boldsymbol{r}_i - \boldsymbol{R}_k|)/\lambda)\hat{\boldsymbol{r}}_{ki}. \quad (3)$$

Here, Θ is the step function, f_p is the maximum pinning force, r_p is the pinning force range which is fixed at $r_p = 0.3\lambda$, and $\hat{\boldsymbol{r}}_{ki} = (\boldsymbol{R}_k - \boldsymbol{r}_i)/|\boldsymbol{R}_k - \boldsymbol{r}_i|$. All lengths, fields, and force are in units of λ, Φ_0/λ^2 and $f_0 = \Phi_0^2/8\pi^2\lambda^3$, respectively.

Simulations were performed on the system of size $L^2 = 20 \times 20$ with periodic boundary conditions in both directions. The driving force $\boldsymbol{F}$ is assumed to be along the x direction. The superconductor sample had periodic distribution of size $L_p \times L$ pinned region and unpinned region of size $(L - L_p) \times L$ (see Fig. 1). Each simulation was started from a random initial configuration of the vortex positions and pinning center positions. The first 50 000 MD steps were typically discarded to assure achievement of a steady state of vortex motion and consequent 20 000 MD steps were used to measure the velocity of vortices and other quantities. Each MD step assured that every vortex tried to occupy a new site.

The mean velocity of the vortices is described by the drift velocity of the vortices in the direction of the driving force $\boldsymbol{F}$ given by

$$v_F = \langle (1/N_v)\sum_{i=1}^{N_v}(\boldsymbol{v}_i \cdot \hat{\boldsymbol{F}}) \rangle. \quad (4)$$

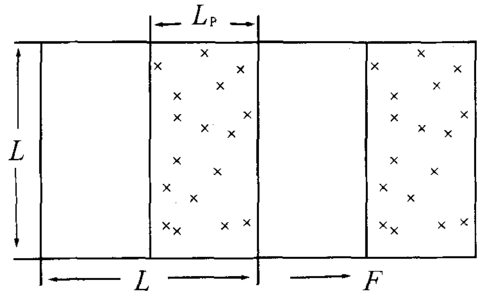

Fig. 1 Periodic distribution of pinned region in superconductor. L_p is the size of pinned region along the direction of the driving force F, symbols × represent pinning centers

The angular brackets denote the average over the last 20 000 MD steps and 5 initial configurations. Curves of v_F versus F correspond to the macroscopically measured voltage-current $V(I)$ curves.

Faleski et al. (1996) showed that the value F_c is clearly nonzero for $N_p > N_v$ for system with random pinning centers. Therefore in this paper, we choose $N_p/N_v = 5$. The pinning region is smaller than L, i.e., $L_p \leqslant L$. The case $L_p = L$ corresponds to a normal system of random pinning centers which is widely used in many simulations (Cao et al., 1999; Jensen et al., 1996; Faleski et al., 1996). We worked with a fixed vortex number of $N_v = 100$ and a tunable maximum pinning force $f_p = 0.5$, 1.0 and 2.0.

RESULTS AND DISCUSSIONS

In order to investigate the influence of the pinning center distribution on the $v_F - F$ curves, we varied the pinning region size L_p from 4 to 20 while keeping L fixed. Results of $f_p = 1.0$ are presented in Fig. 2. For the case of $L_p = L$, one can see that there exist three phases: a pinning glass, a plastic flow regime, and a coherent motion regime and a clearly nonzero critical depinning force F_c. That agrees with previous simulation results (Cao et al., 1999; Faleski et al., 1996). When $L_p < L$, a clearly nonzero critical depinning force F_c still exists but it decreases with the decrease of L_p. That indicates F_c drops when pinning centers are aggregated to a small area. Therefore, the homogeneity of pinning centers helps to enhance the critical electric current of a superconductor. The depinning process becomes more abrupt with increase in the pinning region length L_p. And all these curves converge at large driving force. The $v_F - F$ curves of $f_p = 0.5$ and $f_p = 2.0$ are similar to those of $f_p = 1.0$, the one obvious difference being that the critical depinning force F_c increases with the increase of f_p (see Fig. 4).

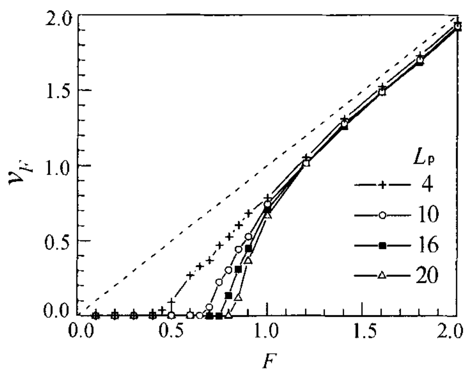

Fig. 2 Plots of the vortex velocity v_F versus the driving force F for different pinned region length L_p at $f_p = 1.0$. The dash line corresponds to $v_F = F$

To correlate the macroscopic response of the vortex array with the details of the microscopic vortex distribution, we studied the spatial distribution of vortex positions. After the vortex system reached a steady state, we recorded the vortex density n_{vp} (vortex number in unit length in the direction of the driving force) in the PR for every MD step. These data were then averaged over the last 20 000 MD steps and 5 initial configurations. Fig. 3 shows the vortex density n_{vp} versus the driving force F for $L_p = 4$, 10 and 16 for $f_p = 1.0$. One can see that n_{vp} is larger than the whole vortex density $n_v = N_v/L = 5$. The relation between n_{vp} and F is governed by the competition between pinning force and vortex interactions. When $F < F_c$, the vortex velocity at steady state $v_F = 0$, we find n_{vp} increases with F. That means some vortices are pulled into the PR by the driving force and then pinned somewhere. As a consequence, these pinned vortices prevent other vortices from entering the PR. When $F > F_c$, some vortices begin to depin, thus n_{vp} decreases with increasing F. We find the driving force corresponding to the maximum of n_{vp} in the $n_{vp} - F$ curve is nearly equal to F_c, and n_{vp} increases with increasing f_p.

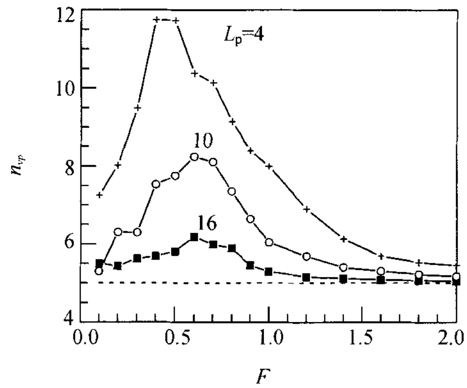

Fig. 3 The dependence of the vortex density n_{vp} in pinned region on the driving force F for different pinned region length L_p at $f_p = 1.0$. The dash line corresponds to vortex density $n_v = 5$

Value n_{vp} as well as its maximum increases with decreasing L_p (see Fig. 3) since the pinning center density in the PR $n_p = N_p/L_p$ increases. We know that a large vortex density will produce large repulsive force because the force range between vortices is much larger than that between vortex and pinning center. For this reason, some vortices, especially those located near the interface of PR and UR, will be subjected to much stronger repulsive force since the vortex density is bigger in the PR. Thus, those vortices will depin easily if the driving force increases and that results in the decrease of the critical force F_c. Therefore, it is reasonable to find F_c decrease with decreasing L_p.

Fig. 4 shows the relation between the critical depinning force F_c and the ratio L/L_p. One can see that F_c is almost in linear proportion to $\ln(L/L_p)$ and can be expressed approximately as

$$F_c = F_c^0 - \alpha \ln(L/L_p). \quad (5)$$

F_c^0 and α for different f_p are calculated using the least square method and the results are listed in Table 1. Value F_c^0, the maximum critical depinning force, or the critical depinning force for the case $L_p = L$, increases with the increase of the maximum pinning force f_p.

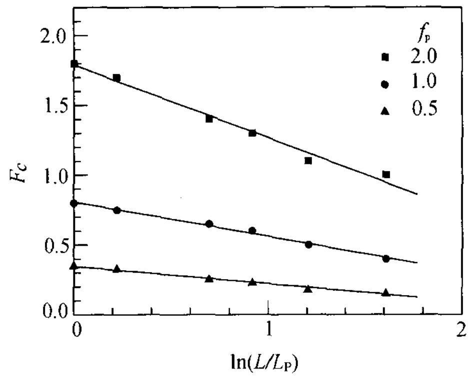

Fig. 4 Plot of the critical depinning force F_c versus ln (L/L_p) for different f_p. The solid lines are the linear fits

Table 1 Values F_c^0, α, F_c^0/f_p, and α/f_p at different f_p

f_p	F_c^0	F_c^0/f_p	α	α/f_p
0.5	0.35	0.7	0.125	0.25
1.0	0.81	0.81	0.249	0.25
2.0	1.79	0.89	0.525	0.26

When all the vortices remain pinned, the total force on a vortex thus consists of the driving force F, pinning force f_p, and force F_v from other vortices. The vortex will remain pinned as long as the following inequality holds (Reichhardt et al., 1997):

$$f_p > F + F_v. \tag{6}$$

That is, the critical depinning force F_c can be determined as

$$F_c = f_p - F_{v\max}, \tag{7}$$

where $F_{v\max}$ is the maximum force one vortex suffered along the driving force. Value $F_{v\max}$ depends on the distribution of vortices, thus depends on the distribution of pinning centers (Dai et al., 1994). Even for $L_p = L$, the distribution of vortices is not uniform because of random pinnings, so $F_{v\max}$ is not zero, therefore, $F_c^0 < f_p$ though it increases with f_p. When $L_p < L$, n_{vp} increases; $F_{v\max}$ increases too. Thus, F_c decreases with the decrease of L_p (Fig.4).

In conclusion, with the dynamic approach we have investigated numerically the influence of the distribution of pinning centers on the pinning of a 2D vortex system. The superconductor sample had periodic structure with PR and UR along the direction of the driving force. Results showed that, at zero temperature, the critical depinning force F_c increases with the increase of L_p, indicating that the homogeneity of pinning centers helps to enhance the critical electric current of the superconductor.

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