Vol 10 No 3, March 2001
1009-1963/2001/10(03)/0229-05

Chinese Physics

© 2001 Chin. Phys. Soc.
and IOP Publishing Ltd

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

LUO MENG-BO(罗孟波)[a], JIAO ZHENG-KUAN(焦正宽)[a],
REN QING-BAO(任清褒)[b], and CHEN QING-HU(陈庆虎)[a]
[a] *Department of Physics, Zhejiang University, Hangzhou* 310027, *China*
[b] *Department of Physics, Lishui Teacher College, Lishui* 323000, *China*

(Received 13 October 2000)

Numerical study of the influence of the distribution of pinning centres on the dynamics of a two-dimensional vortex system is performed. The superconductor sample has a periodic structure with a pinned region of length L_p and an unpinned region of length L_x-L_p along the direction of driving force (Lorentz force). Results show that, at zero temperature, the critical force F_c increases with the increase of L_p, indicating that the homogeneity of pinning centres helps to enhance the critical electric current of the superconductor. At large driving forces, vortex static channels form in the pinned region even for $L_p < L_x$.

Keywords: pinning, vortex lattice, dynamics
PACC: 7460G, 7460J

I. INTRODUCTION

The physics of a vortex lattice (VL) in type II superconductors has been a central interest since the beginning of high-T_c superconductor research. The dynamics of VL is governed by the competition between vortex interactions, which favour the formation of an ordered Abrikosov lattice, and pinning by a random distribution of material defects, which favour a disordered VL. Vortex pinning by defects has recently been the subject of intense investigations because of its ability to immobilize vortices, reduce dissipation effects and create high critical currents.[1]

Particularly, the dynamics of driven VL interacting with quenched random pinning has attracted considerable attention.[2] 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 transition can be described as a critical phenomenon in terms of scaling laws and critical exponents.[3] The critical force F_c is related to the critical electric current density J_c of a real superconductor. It is demonstrated that F_c or J_c is affected by many factors, such as pinning strength, pinning centre density, temperature and field.[2−5] Above the critical force F_c, the vortices form a pattern of pinned and unpinned regions, often described as an incoherent or a plastic flow.[1] At large driving forces, disorder would produce little effect since the pinning force on a given vortex varies rapidly. Thus by increasing the driving force beyond some critical values a change from incoherent to coherent vortex motion occurs and the vortex system forms a moving glass.[6,7] Several experiments indeed suggest that a fast moving VL is more ordered and often forms static channels.[8,9]

Numerical simulations on the behaviour of the VL in an inhomogeneous environment help to establish a correlation between the structure of microscopic defects and the macroscopic response of the system. Most simulations have been devoted to the simplest case of a two-dimensional (2D) vortex system interacting with point-like pinnings, which describes the behaviour in superconducting thin films or materials with columnar defects created by heavy-ion irradiation.

In this work, we will address the influence of pinning centre distribution on the dynamics of a 2D vortex system. In a real superconductor, the distribution of pinning centres is usually inhomogeneous. Our simulation has been devoted to a simple case: the pinned region (PR) and unpinned region (UR) are arrayed periodically in the direction of the driving force. This kind of periodic structure has been prepared for some special cases by heavy-ion irradiation.[10,11] In the simulations, we investigate the dependence of the vortex

*Project supported by the Ministry of Science and Technology of China (NKBRSF-G19990646) and the Provincial Scientific Foundation of Zhejiang, China (199031).

velocity on the driving force by changing the size of the PR while keeping the number of pinning centres constant.

II. MODEL

We employ overdamped molecular dynamics (MD) simulation at zero temperature to study 2D interacting vortices in the presence of point-like pinnings,[12,13]

$$\eta\frac{\mathrm{d}\boldsymbol{r}_i}{\mathrm{d}t}=\sum_{j\neq 1}^{N_\mathrm{v}}\boldsymbol{F}_\mathrm{vv}(\boldsymbol{r}_i-\boldsymbol{r}_j)+\sum_{k=1}^{N_\mathrm{p}}\boldsymbol{F}_\mathrm{pv}(\boldsymbol{r}_i-\boldsymbol{R}_k)+\boldsymbol{F}. \quad (1)$$

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

$$\boldsymbol{F}_\mathrm{vv}(\boldsymbol{r}_i-\boldsymbol{r}_j)=f_0K_1(|\boldsymbol{r}_i-\boldsymbol{r}_j|/\lambda)\hat{\boldsymbol{r}}_{ij}, \quad (2)$$

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 cut-off is placed on $K_1(r/\lambda)$ after it reaches an extremely small value at $r=6\lambda$. The pinning force is taken to be

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

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

Simulations are performed on the system of size $L^2=L_x\times L_y$ with periodic boundary conditions in both directions. The driving force $\boldsymbol{F}$ is assumed to be along the x direction. The superconductor sample has a periodic distribution with a pinned region of size $L_\mathrm{p}\times L_y$ and an unpinned region of size $(L_x-L_\mathrm{p})\times L_y$. Each simulation starts with a different random initial configuration of the vortex positions and pinning centre positions. We discard the first 50 000 MD steps to assure achievement of a steady state of vortex motion and use the consequent 20 000 MD steps for measurements of the velocity of vortices and other quantities. Each MD step ensures every vortex attempts to occupy a new site.

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

$$\nu_F=<(1/N_\mathrm{v})\sum_{i=1}^{N_\mathrm{v}}(\boldsymbol{v}_i\cdot\hat{\boldsymbol{F}})>. \quad (4)$$

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

Faleski *et al.*[2] showed that the value F_c is clearly nonzero for $N_\mathrm{p}>N_\mathrm{v}$ so, in this paper, we choose $N_\mathrm{p}/N_\mathrm{v}=5$. In each simulation, the vortex density N_v/L^2 is fixed to 0.25, and L_y is also set to be 20. The length of pinning region L_p is smaller than L_x, $L_\mathrm{p}\leq L_x$. The case $L_\mathrm{p}=L_x$ corresponds to a conventional system of random pinning centres, which is widely used in computer simulations.[2,4,5,7]

III. RESULTS AND DISCUSSIONS

In order to investigate the influence of the pinning centre distribution on the curves of the vortex velocity ν_F versus the driving force F, the pinning region size L_p is varied from 4 to 20, while L_x is fixed as L_x=20. Results for f_p=2.0 are presented in Fig.1. For the case of $L_\mathrm{p}=L_x$, one can see that three phases exist: a pinning glass, a plastic flow regime, and a moving vortex glass and a clearly nonzero critical pinning force F_c. This agrees with previous simulation results.[2,5] When $L_\mathrm{p}<L_x$, a clearly nonzero critical pinning force F_c still exists, but it decreases with the decrease of L_p. This indicates that F_c drops when pinning centres are aggregated to a small area. Therefore, the homogeneity of pinning centres helps to enhance the critical electric current of the superconductor. Moreover, the depinning process becomes more abrupt with the increase of the pinning region length L_p. And all these curves converge at large driving force. The $\nu_F\sim F$ curves of f_p=0.5 and f_p=1.0 are similar to that of f_p=2.0; the one obvious difference is that the critical pinning force F_c increases with the increase of f_p (see Fig.2). For this reason, these curves are not shown here.

Figure 2 shows the relation between the critical pinning force F_c and the ratio L_x/L_p for different pinning force f_p while L_x is fixed as L_x=20. One can see that F_c is almost in linear proportion to $\ln(L_x/L_\mathrm{p})$ and can be expressed approximately as

$$F_\mathrm{c}=F_\mathrm{c}^0-\alpha\ln(L_x-L_\mathrm{p}). \quad (5)$$

The value F_c^0, the maximum critical pinning force, or the critical force of the case $L_p = L_x$, increases with the increase of the maximum pinning force f_p. We have also checked for the finite size effects using system size from 20×20 to 40×20, but keeping the ratio N_p/N_v, the vortex density N_v/L^2, and f_p fixed. The result of f_p=2.0 is shown in Fig.3. It indicates that F_c^0 is almost of size independence.

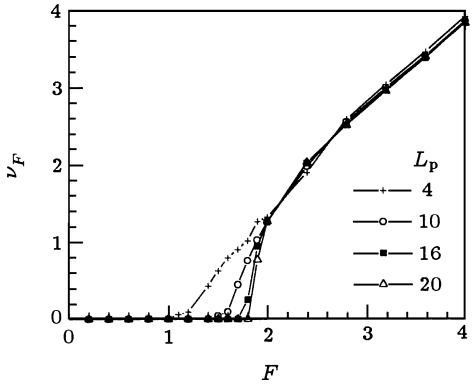


Fig.1. Plots of the vortex velocity v_F versus the driving force F for different pinning region length L_p. System size is 20×20.

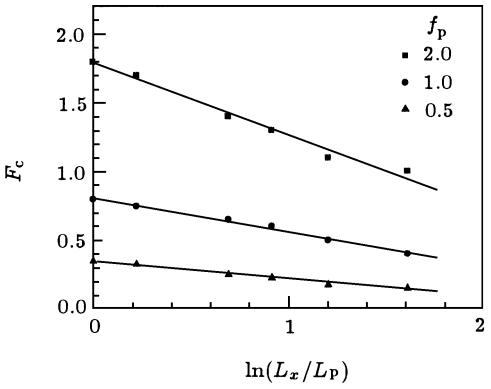


Fig.2. Plot of the critical pinning force F_c versus $\ln(L_x/L_p)$ for different f_p. L_x is fixed as 20. The solid lines are the linear fits.

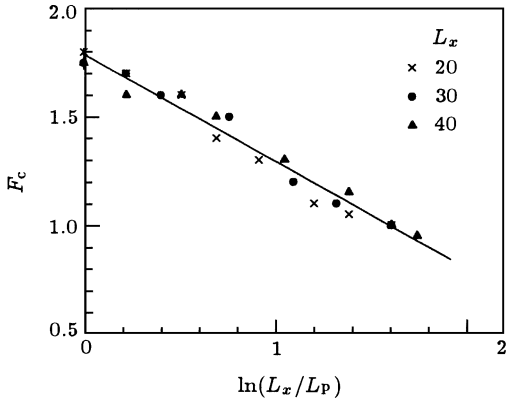


Fig.3. Plot of the critical pinning force F_c versus $\ln(L_x/L_p)$ for f_p=2.0. The solid line is a linear fit.

To correlate the macroscopic response of the VL with the details of the microscopic vortex distribution, we have performed a variety of visualizations and studied the spatial distribution of vortex positions. After the vortex system reaches a steady state, we record the vortex density n_v (vortex number per unit length) in the direction of the driving force for every MD step. These data are then averaged over the last 20000 MD steps and five initial configurations. Figure 4 shows the vortex densities n_v versus site x for L_x=20, L_p=10 at various driving forces for the case f_p=2.0.

At a small driving force, $F \leq 1.5$, the vortex are almost immobile (see Fig.1). One can see that, from Fig.4, the maximum density n_v is at site x=11, indicating that many more vortices are pinned in the PR near the interface. These pinned vortices near the interface would prevent other vortices from crossing over the interface. So, there are still some vortices remaining in the UR. The values n_v in the UR decrease with increasing F, indicating that more and more vortices enter the PR with the increase of F. Comparing these curves, we find the maximum value of n_v initially increases with the driving force, then it nearly remains unchanged for a large scale of F (from F=0.5 to F=1.5). Therefore, with the increase of the driving force, the vortices are redistributed after some vortices are pulled into the PR. The reason may be that a large vortex density will produce a large repulsive force because the force range between vortices is much larger than that between the vortex and pinning centre. Since the vortex densities are large in the PR, some vortices, especially those located near the interface, suffer a much stronger repulsive force. Thus, those vortices would move into the PR with the increase of F.

As the driving force goes beyond critical force F_c, the density n_v in the PR drops with F (see the inset in Fig.4). At large F, for example F=3.0 in this situation, no peak is found evidently and the density n_v in the PR is only slightly bigger than that in the UR. Thus, the difference of vortex distribution between PR and UR almost disappears, and then we see that the vortex velocities are almost the same for different L_p at large F (Fig.1).

When all the vortices remain pinned, the total force on a vortex thus consists of the driving force F, pinning force f_p, and the force F_v from other vortices. The vortex will remain pinned as long as the following inequality holds[12]:

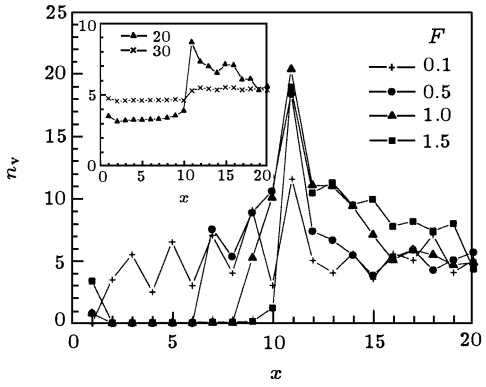


Fig.4. The dependence of the vortex density n_v (vortex number in unit length in the x direction) on site x. The driving force is also in the x direction. System size is 20×20, the pinned region length L_p=10 and pinning centres locate from x=10 to x=20 (or from x=11 to x=20 in discrete).

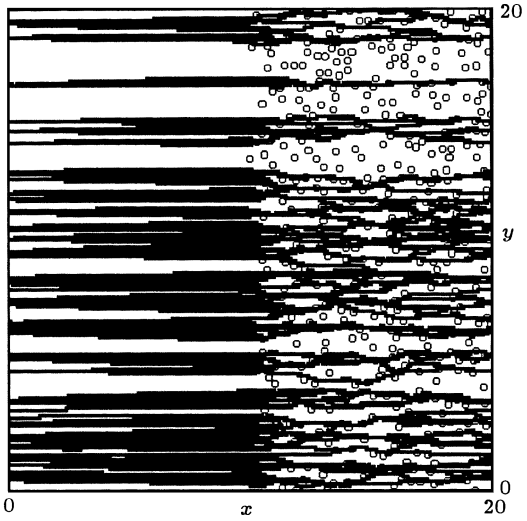


Fig.5. The static channels in the steady state for L_x=20, L_p=10 and F=3.0. Pinning sites are indicated by open circles which locate from x=10 to x=20, while the maximum force f_p=2.0.

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

That is, the critical force F_c can be determined as

$$F_c = f_p - F_{vmax} \tag{7}$$

where F_{vmax} is the maximum force along the driving force that one vortex suffers. The value F_{vmax} depends on the distribution of vortices, and thus depends on the distribution of pinning centres.[14] Even for $L_p = L_x$, the distribution of vortices is not uniform because of random pinning, so F_{vmax} is not zero, and thus we have $F_c^0 < f_p$, though it increases with f_p (Fig.2). When $L_p < L_x$, we find that the vortex density n_v in the PR increases with the decrease of L_p and, as a result, F_{vmax} increases too. Therefore, F_c decreases with the decrease of L_p.

We have also checked whether the static channels still exist at a high driving force for the case of aggregated pinning centres, $L_p < L_x$. For the case of L_x=20, L_p=10 and f_p=2.0, we divide the sample into a 200×200 grid to identify the vortex channels. When a vortex enters a grid element, the counter associated with that grid element increases. All the grid elements that are visited at least once are considered part of the channel network. Indeed, we see the static channels in the steady state at large velocity. Figure 5 demonstrates that the moving vortices really form static channels even if the pinning centres are aggregated to a smaller area. But we find the width of these channels in the PR is narrower than that in the UR. Due to the interaction between vortices, the channels in the UR become wider and wider along the direction of the driving force. Thus, if the UR is sufficiently long in the x direction, these channels will meet each other and the channels disappear near the interface. But in the PR, vortices will still form narrow static channels. Thus, we can conclude that it is the pinning that attracts vortices to form vortex channels.

In conclusion, with a dynamic approach we have investigated numerically the influence of the distribution of pinning centres on the dynamics of a 2D vortex system. The superconductor sample has a periodic structure with PR and UR along the direction of the driving force. Results show that, at zero temperature, the critical force F_c increases with the increase of L_p, indicating that the homogeneity of pinning centres helps to enhance the critical electric current of the superconductor. The critical pinning force F_c is linearly proportional to $\ln(L_x/L_p)$ and can be expressed approximately as $F_c = F_c^0 - \alpha \ln(L_x/L_p)$. The values F_c^0 depend on the maximum pinning force f_p, but are almost size independent. At a small driving force, the density of vortex in the PR is higher. At a large driving force, the difference of vortex density between PR and UR dies away with the increase of the driving force. Also at large driving force, vortex static channels in the PR are found even for $L_p < L_x$.

References

[1] Blatter G, Feigel'man M V and Geshkenbein V B 1994 *Rev. Mod. Phys.* **66** 1125

[2] Faleski M C, Marchetti M C and Middleton A A 1996 *Phys. Rev.* B **54** 12427

[3] Higgins M J and Bhattacharya S 1996 *Physica* C **257** 232

[4] Cao Y G and Jiao Z K 2000 *Chin. Phys.* **9** 199

[5] Cao Y G and Jiao Z K 2000 *Chin. Phys.* **9** 61

[6] Giamarchi T and Le Doussal P 1996 *Phys. Rev. Lett.* **76** 3408.

[7] Moon K, Scalettar R T and Zimányi G T 1996 *Phys. Rev. Lett.* **77** 2278

[8] Yaron U, Gammel P L and Huse D A 1994 *Phys. Rev. Lett.* **73** 2748

[9] Hellerqvist M C, Ephron D and White W R 1996 *Phys. Rev. Lett.* **76** 4022

[10] Pruymboom A, Kes P H and van der Driff E 1988 *Phys. Rev. Lett.* **60** 1430

[11] Pastoriza H and Kes P H 1995 *Phys. Rev. Lett.* **75** 3525

[12] Reichhardt C, Olson C J and Nori F 1997 *Phys. Rev. Lett.* **78** 2648

[13] Olson C J, Reichhardt C and Nori F 1998 *Phys. Rev. Lett.* **81** 3757

[14] Dai H, Yoon S and Liu J *et al* 1994 *Science* **265** 1552