Crossover between the classical friction and the nano-scale friction investigated by the transient dynamics of vortices in \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\) thin films

D Nakamura, S Kitamura and A Maeda
Department of Basic Science, the University of Tokyo, Tokyo, 153-8902, Japan
E-mail: dnakamura@maeda1.c.u-tokyo.ac.jp

Abstract. We investigated the dynamics of driven vortices in high-\(T_c\) superconductor from the viewpoint of the physics of friction. First of all, for all samples, we found the obvious waiting-time dependence of the maximum static friction force which is proportional to the critical current density, below the glass-liquid transition line. This indicates that the dynamics of vortices is like the nano-scale(microscopic) friction, where the relaxation occurs frequently. As temperature decreased, the waiting-time dependence dissapeared, impling that the vortex dynamics became that of classical(macroscopic) friction, where the relaxation rarely occurs. The crossover line of the relaxation phenomena depend on the bridge size. From the results obtained in this paper, we propose a universal parameter which discriminates the macroscopic friction from the microscopic friction.

1. Introduction
The dynamics of driven vortices in high-\(T_c\) superconductors has been investigated extensively, in terms of the variety of non-stationary driven state of the elastic objects[1]. Vortices can escape from the pinning potential in a sample by applying sufficient external driving current density above the critical value, \(j_c\). In addition, the thermal fluctuation causes thermally assisted flux flow (TAFF)[2] to the motion of vortices. As a consequence, vortices move with a finite net velocity and relax into the stable state even below \(j_c\). Below the glass-liquid phase transition temperature, \(T_g\), vortices feel the pinning force collectively[3], and the timescale of the relaxation process in the glassy phase becomes very long owing to the existence of metastable states. Thus, aging and memory effects are observed in vortices in superconductors[4, 5, 6]. Similar effects have been observed in charge density wave[7] and domain walls in ferromagnets[8].

On the other hand, scientific challenges to elucidate the physics of friction have recently made progress in some aspects[9, 10]. There is the empirical law of friction known as the Amontons-Coulomb’s law, where the kinetic friction force, \(F_k\), is independent of the sliding velocity and the maximum static friction force, \(F_s\), is constant. However, in some cases \(F_k\) slightly depends on the velocity at low velocities, and \(F_s\) depends on the waiting time, \(t_w\), which is the intermission time of a repetitively applied driving force[11, 12, 13]. The deformation and the destruction of the microscopic asperity of the interface are considered to be the candidates for the origin of deviations from the Amontons-Coulomb’s law[14]. In this stand points, the classical friction phenomena, which obeys the Amontons-Coulomb’s law, occurs at relatively flat (macroscopic) interface, while the relaxation process by the large thermal fluctuation plays a more important
Table 1. Sample profiles. The size between electrodes, $T_c$, and the estimated number of vortices in bridged region at 1.0 T are shown.

| Sample | Size ($\mu$m × $\mu$m) | $T_c$ (K) | Number of vortices at 1.0 T |
|--------|------------------------|-----------|----------------------------|
| #A     | 11.1 × 51.6            | 35.89     | 2.75×10^5                  |
| #B     | 43.8 × 87.5            | 38.91     | 1.85×10^6                  |
| #C     | 95.1 × 110             | 28.76     | 3.46×10^6                  |

role at the nano-scale (microscopic) interface. However, no consensus has been achieved for the detailed mechanism of the relaxation and the energy dissipation at microscopic interface.

We utilize the dynamics of driven vortices to investigate these unsettled problems in the physics of friction. Our approach does not contain either deteriorations or damages of the sample, so we can repeat experiments under the same environment. This is the significant advantage because the measurement at the real microscopic interface is often influenced by the existence of the wear, the junction growth by the adhesion, contamination materials, etc. Explicit correspondence has been made as follows[15, 16]. The static friction, $F_s$, is equal to the Lorentz force induced by $j_c$; $F_s = j_c\Phi_0$, where $\Phi_0$ is the flux quantum. On the other hand, for the dry friction we can obtain the kinetic friction, $F_k$, by measuring the $I$-$V$ characteristics of driven vortices and extracting the interaction to the pinning force; $F_k = j\Phi_0 - \eta v$, where $\eta$ is the viscous coefficient. We previously observed the strongly velocity-dependent $F_k$ for wide velocity range in high-$T_c$ superconductors La$_{2-x}$Sr$_x$CuO$_4$ and Bi$_2$Sr$_2$CaCu$_2$O$_y$, which implies that the dynamics of vortices can be interpreted as the microscopic friction, where the thermal fluctuation dominates and the relaxation process occurs rapidly[16, 17]. As for the static friction in La$_{2-x}$Sr$_x$CuO$_4$, $F_s(t_w)$ also exhibited a non-Amontons-Coulomb’s behavior, and $F_s(t_w)$ curve changed in the $H$-$T$ phase diagram[18]. We found that the difference of the size of coherently moving vortex lattice causes such a change, because the size of the vortex bundle in the glass phase increases with decreasing temperature. In this paper, we aim to clarify what parameter classifies the different friction phenomena from the microscopic one to the macroscopic one. Therefore, we changed the size of the sample by fabricating the bridge-type structure and measured $F_s(t_w)$ to investigate an effect of the size of coherently moving vortex lattice.

2. Experiment

Films of the optimally doped La$_{1.85}$Sr$_{0.15}$CuO$_4$ with 3000 Å-thickness were prepared by the pulsed laser deposition technique[19]. An 0.5 mm thick LaSrAlO$_4$(001) substrate was used to minimize the mismatch of the lattice constant. The size between the voltage electrodes, $T_c$, and the estimated number of vortices at 1.0 T are shown in Table 1.

Magnetic fields were applied along the $c$-axis by field-cooling conditions to avoid the non-uniformity of vortex density. For the $I$-$V$ characteristics measurements we used an ordinary four-probe method. A sawtooth-like pulsed electrical current with a finite waiting time, $t_w$, was applied to obtain the transient response of vortices. By comparing the critical current densities for different $t_w$, we obtained $t_w$ dependence of a maximum static friction force, $F_s(t_w)$, in terms of the dynamics of vortices. We also applied a rectangular pulsed current separately, and changed its duration time and $t_w$ in order to check the joule-heating effect. Empirically, we found that the heating effect is almost negligible below 0.5 W. In our measurements, typical duration time of a sawtooth-like pulsed current was 0.125 ms and the maximum power generated in the sample was estimated about 1 μW. Thus, we safely concluded that the obtained $F_s(t_w)$ was not caused by the heating effect of samples.
3. Results and discussion

Figure 1 shows the $t_w$ dependence of the critical current density, which is proportional to the maximum static friction force; $F_s(t_w) = j_c \Phi_0$. Since the absolute value of $F_s$ increased largely as temperature decreased, we took the normalized $F_s$ value at the maximum $t_w$ (typically 30 sec.), $F_s(t_w)/F_s(\text{Max } t_w)$, as the vertical axis in figure 1. As a criteria to determine $j_c$, we set the threshold value of voltage 0.5 $\mu$V, which is almost the minimum voltage obtained from the digital oscilloscope. Both samples #A and #B showed the obvious relaxation near $T_g$ (figures 1(a) and 1(b)), while no relaxation took place at lower temperatures (figures 1(c) and 1(d)). We also found the same feature for the sample #C (not shown in the figure).

At first, we discuss the results near $T_g$. Common to both samples #A and #B, the logarithmic $t_w$ dependence emerged at rather long $t_w$ range, which is similar to the our previous results [18]. The origin of these logarithmic responses is known to be TAFF, where the pinning potential depends linearly on the current density [20]. From the viewpoint of the friction, the logarithmic relaxation can be also seen in the friction at the solid-solid interface, where the increase of the real contact area takes place by the plastic deformation of the interface [12]. Therefore, it is considered to be a common character of the microscopic interface, where the plastic deformation takes place and the interaction between interface becomes strong. It should be noted that the slope of the logarithmic dependence was different in the $H-T$ phase diagram (thick bands are for guides to the eye) in sample #A, while in sample #B the slope of $t_w$ dependence did not change with the temperature and the magnetic field largely.

On the other hand, any relaxation can not be observed in both samples at lower temperatures (figures 1(c) and 1(d)). This effect was not observed before we fabricated the sample into the bridge-type structure [18], impling that this is due to the enlarged pinning strength at the edge of the sample. When the size of the coherently moving vortex bundles becomes comparable to the size of the bridge region in a sample, the vortex bundles are effectively pinned, which makes any relaxation to take place hardly.

Furthermore, we found the size dependence of the crossover of the relaxation phenomena. Figure 2 shows that there is a the bridge-width ($w$) dependent region where the relaxation process...
cannot be seen (closed symbols) in the reduced temperature, \( t = T/T_g \), vs \( w \) diagram. The thick line \((\propto t^{1.5})\) is a guide to the eye, which indicates that the smaller the sample size becomes, the smaller the relaxation region becomes. It suggests that the size of coherently moving objects plays an important role for the relaxation. Therefore, there must be a universal parameter which discriminates the classical (macroscopic) friction from the nano-scale (microscopic) friction. This parameter includes the size of the vortex bundle and the probability of the depinning by TAFF. Based on the results presented above, we believe that the parameter such as \( R_c^{-1} \exp[-U/kT_{\text{eff}}] \) can be a candidate for such a universal parameter, where \( R_c \) is the radius of the vortex bundle, \( U \) is the activation energy, and \( T_{\text{eff}} \propto T/L^3 \) is the effective temperature taking into account of the effect of the system size \( L \) of the bridge part. Detailed discussion is in progress.

4. Conclusion

We investigated the dynamics of driven vortices in high-\( T_c \) superconductor in terms of the physics of friction. The transient responses of driven vortices were measured in La\(_{1.85}\)Sr\(_{0.15}\)CuO\(_4\) thin films with different bridge sizes. We found the logarithmic waiting-time dependences of the maximum static friction force near \( T_g \), which can be understood by the TAFF picture, whereas the relaxation disappeared with decreasing temperature moreover. This suggests that the size of the coherently moving vortices becomes comparable to that of bridge part, and vortices are strongly pinned by the edge of the sample, collectively. From our results, we proposed a universal parameter which distinguishes the macroscopic friction from the microscopic friction.

Acknowledgments

We thank S. Komiyama for supports in the instrumentation. D. Nakamura also thanks to the Japan Society for the Promotion of Science for the financial support.

References

[1] Kuriki S, Hirano S, Maeda A and Kiss T 2003 Vortex in high-\( T_c \) superconductors Vortex Electronics and SQUIDs ed T Kobayashi (Springer Verlag.) 5-51; Blatter G, Feigel'man M V, Geshkenbein V B, Larkin A I and Vinokur V B, Larkin A I and Vinokur V M 1994 Rev. Mod. Phys. 66 1125
[2] Anderson P W 1962 Phys. Rev. Lett. 9 309; Anderson P W and Kim Y B 1964 Rev. Mod. Phys. 36 39; Kes P H, Aarts J, van den Berg J, van der Beek C J and Mydosh J A 1989 Supercond. Sci. Technol. 1 242
[3] Larkin A I and Ovchinnikov Y N 1979 J. Low Temp. Phys. 34 409
[4] Du X, Li G, Andrei E Y, Greenblatt M and Shuk P 2007 Nat. Phys. 3 111
[5] Xiao Z L, Andrei E Y and Higgins M J 1999 Phys. Rev. Lett. 83 1664
[6] Henderson W, Andrei E Y and Higgins M J 1998 Phys. Rev. Lett. 81 2352
[7] Ogawa N and Miyano K 2002 J. Phys. IV France 12 Pr9-83
[8] Alberici-Kious F, Bouchaud J-P, Cugliandolo L F, Doussineau P and Levelut A 2000 Phys. Rev. B 62 14766
[9] Persson B N J 1998 Sliding Friction (Berlin: Springer)
[10] Ed Blushan B 2004 Handbook of Nano-technology (Berlin: Springer)
[11] Yoshizawa H and Israelachvili J 1993 J. Phys. Chem. 97 11300
[12] Scholz H C and Engelder T J 1976 Int. J. Rock Mech. Men. and Geomech. Abstr. 13 149
[13] Nitta T, Kato H, Haga H, Nemoto K and Kawabata K 2005 J. Phys. Soc. Jpn. 11 2875
[14] Bowden F P and Tabor D 1986 The Friction and Lubrication of Solids (Oxford: Clarendon Press)
[15] Matsukawa H and Fukuyama H 1994 Phys. Rev. B 49 17286
[16] Maeda A, Inoue Y, Kitano H, Savel’ev S, Okuyasu S, Tsukada I and Nori F 2005 Phys. Rev. Lett. 94 077001
[17] Maeda A and Nakamura D 2007 J. Phys.: Conf. Ser. 89 012020
[18] Nakamura D, Kubo T, Kitamura S, Gomez L B, Maeda A, Konczykowski M and van der Beek C J 2007 J. Phys.: Conf. Ser. 89 012021
[19] Tsukada I 2004 Phys. Rev. B 70 174520
[20] Beasley M R, Labusch R and Webb W W 1969 Phys. Rev. 181 682