We systematically investigated the waiting-time dependence of the maximum static friction force, $F_s(t_w)$, using the dynamics of driven vortices in a high-$T_c$ superconductor as a model system. $F_s(t_w)$ was measured in La$_{2-x}$Sr$_x$CuO$_4$ thin films with different structures, sample sizes and pinning force. We found that $F_s(t_w)$ by thermal fluctuation is strongly affected by the pinning strength, the vortex bundle size and the system size. Based on these results, we found crucial conditions to determine the validity of the Amontons–Coulomb’s law, and proposed a criterion.

Some figures in this article are in colour only in the electronic version.

1. Introduction

The physics of friction has attracted both scientists and engineers for more than 500 years [1, 2]. The empirical law of friction is known as the Amontons–Coulomb’s (AC) law, describing (1) the friction is proportional to the normal load, (2) the kinetic friction force, $F_k$, is independent of the sliding velocity, $v$, (3) the maximum static friction force, $F_s$, is constant. The true contact point at the interface is one concept to explain the AC law [3]. The increase of the area of true contact points as a function of the normal load can lead to law (1). Law (2) can be explained by the mechanism that the kinetic friction arises from the motion of true contact points, whose velocities do not almost depend on the macroscopic velocity of the sliding object. Therefore, the investigation of not only the macroscopic motion of the sliding object but also the dissipation mechanism at the interface is important to elucidate the physics of friction. In addition, the AC law represents only very limited situations in the friction phenomena. In reality, $F_k$ generally depends on the velocity, and $F_s$ depends on the waiting time, $t_w$, which is the intermission time of a repetitively applied driving force. If plastic deformation of the true contact points takes place, there should exist some timescale for the deformation, which seems to cause $F_s(t_w)$. However, the relation among laws (1)–(3) is not still clear. For example, Heslot et al reported that there is some scaling relationship between $F_k(v)$ and $F_s(t_w)$ [4]. Therefore, $F_s(t_w)$ does not always come from the deformation of the true contact points, and the motion of debris [5] is also considered to affect $F_s(t_w)$. In fact, $F_s(t_w)$ was found not only in the friction at the macroscopic system such as the solid–solid interface of a massive block [6] and the soft materials [7], but also in the friction at the lubricated microscopic interface, which is atomically smooth [8]. In this sense, we will focus on laws (2) and (3) below, and will use the term, ‘AC like friction’ only in the senses of (2) and (3). Scientific challenges to elucidate the physics of friction have recently made progress in some aspects from the microscopic viewpoint [8, 9]. However, the comprehensive understanding of the friction phenomena in any spatial scales and the hierarchy in the friction phenomena are still completely open issues. This indicates that the experimental parameters to describe the condition of the interface are more appropriately selected and need to be systematically controlled.

We have utilized the dynamics of driven vortices in high-$T_c$ superconductors [10, 11] to investigate these unsettled subjects in the physics of friction [12, 13], since it has many common aspects to the physics of friction. In the physics of friction, the object starts to move above $F_s$ and its dynamics has various characteristics, such as the stationary motion, the
stick-slip motion, and the intermediate motion between them. Even if $F < F_c$, thermal fluctuation causes microscopic relaxation of the interface because of the randomness and the multi-internal degrees of freedom. As a result, various kinds of ageing effects and memory effects are often observed [1, 2]. On the other hand, in the case of the dynamics of driven vortices, vortices can escape from the pinning potential in a sample by applying sufficient external driving current density above the critical value, $j_c$. It is also possible that even the effect of the vertical load is indirectly included in the interaction force between the driven vortices and pinning centres. In addition, thermal fluctuation causes vortices to move with a finite net velocity even below $j_c$ and the vortices relax into the more stable position. As a consequence, the ageing effects and the memory effects are also commonly observed in the vortices in superconductors [14–16]. Similar effects have been also observed in other quantum condensates, such as the charge density wave [17] and domain walls in ferromagnets [18] (For details, see table I of [12]). Moreover, we can systematically tune the condition of the interface by ferromagnets [18] (For details, see table I of [12]). Moreover, we can systematically tune the condition of the interface by ferromagnets [18] (For details, see table I of [12]). Moreover, we can systematically tune the condition of the interface by ferromagnets [18] (For details, see table I of [12]).

The dynamical properties, including plastic flow, are observed. A notable merit of our approach is that it does not involve either deterioration or damage in a sample during experiments. We can repeat experiments under the same external environment, because an interface in solid–solid friction corresponds to the part where the vortices and pinning centres interact in the driven vortices in the superconductors. This is a significant advantage, because the measurement at the real microscopic interface is often influenced by the existence of wear, the junction growth by adhesion, and contamination materials, etc. By measuring the $I$–$V$ characteristics of the driven vortices, explicit correspondence to the physical quantities shown up in the friction at the solid–solid interface has been obtained as follows [24, 12]. $F_s$ is equal to the critical Lorentz force at $j_c$: $F_s = j_c \Phi_0$, where $\Phi_0$ is the flux quantum. On the other hand, we can obtain $F_k$ by extracting the pinning force, which is the driving force minus the viscous drag in the steady state: $F_k = j \Phi_0 - \eta v$, where $\eta$ is the viscous drag coefficient. We previously observed the strongly velocity-dependent $F_k$ for a wide velocity range in high-$T_c$ superconductors La$_{2-\delta}$Sr$_\delta$CuO$_4$ and Bi$_2$Sr$_2$CaCu$_2$O$_y$, and we could scan various regions in the dynamic phase diagram of the driven vortices from AC type to non-AC type by tuning $B$, $T$, and also the pinning strength [12, 13]. This result suggests that the drastic change of the memory effect should be also observed in the same systems. Furthermore, we expect that the criteria for the validity of the AC law will be obtained by comparing the results of $F_s(t_w)$ with $F_k(v)$. Therefore, in this paper, another key phenomenon for the friction, $F_k(t_w)$, was investigated in vortex systems. By irradiating the columnar defects in the sample, we changed the strength of the pinning force. This corresponds to the increase of the interface interaction, and may also correspond to the change in the surface roughness in solid–solid friction tests, since it is well established that the columnar defects act as pinning centres with higher dimensions than point defects and that they did alter the equilibrium phase diagram of vortex matter. In addition, we changed the sample size by fabricating the bridge-type structure with different sizes. This corresponds to the change in the interface interaction in solid–solid friction.

### Table 1. Sample profiles. The nominal carrier concentration, $x$, the width, $w$, and the distance, $d$, between the voltage electrodes and the superconducting transition temperature, $T_c$, are shown. R, B, and C represent the rectangular-type structure, the bridge-type structure, and the bridge-type structure with columnar defects, respectively.

| Sample | $x$ (\text{\textmu}m) | $w$ (\textmu m) | $d$ (\textmu m) | $T_c$ (K) |
|--------|----------------|----------------|----------------|-----------|
| #R1    | 0.12           | 1470           | 660            | 35.20     |
| #R2    | 0.15           | 1180           | 210            | 35.06     |
| #B1    | 0.15           | 11.1           | 51.6           | 35.89     |
| #B2    | 0.15           | 43.8           | 87.5           | 38.91     |
| #B3    | 0.15           | 95.1           | 110.0          | 28.76     |
| #C1    | 0.15           | 40.0           | 90.0           | 35.11     |

2. Experiments

Films of the underdoped ($x = 0.12$) and the optimally doped ($x = 0.15$) La$_{2-\delta}$Sr$_\delta$CuO$_4$ with 3000 Å-thickness on a LaSrAlO$_4$ substrate were prepared by the pulsed laser deposition technique [25]. Three types of thin film were prepared (figure 1(a)). The first type was a thin film with a rectangular-type structure (#R1, #R2). The second type was a thin film with a bridge-type structure (#B1–#B3), fabricated by photolithography and the chemical etching technique. The third type was a bridge-type thin film with columnar defects (#C1), introduced by the irradiation of 5.8 GeV Pb ions parallel to the $c$-axis using the Grand Accélérateur National d’Ions Lourds (GANIL) in Caen, France. The electrodes were made by painting Au paste. The nominal carrier concentration, $x$, the width, $w$, and the distance, $d$, between the voltage electrodes, and the superconducting transition temperature, $T_c$, are shown in table 1.

Magnetic fields were applied along the $c$-axis with field-cooled conditions to avoid possible non-uniformity of the vortex density. Also, we waited about one hour before each experiment to achieve homogeneous distribution of the vortices. A sawtooth-like pulsed electrical current with $t_w$ was applied to obtain the transient response of the vortices, as...
is shown in the top panel of figure 1(b). The bottom panel of figure 1(b) shows the raw data of the experiments. The solid line is the driving current, and the open symbols are the induced voltages in a sample with different waiting times, \( t_\text{w} \). The arrows represent the appearance of finite voltages.

**3. Results and discussion**

We first discuss the results in terms of the physics of driven vortices. Let us start from the results on the samples with the rectangular-type structure (#R1, #R2). Since \( j_\text{c} \) strongly depends on the temperature, we normalized the \( j_\text{c} (t_\text{w}) \) data by \( j_\text{c} \) at the maximum \( t_\text{w} \), \( I_\text{c}^\text{M} \). Figure 2 shows the waiting-time dependence of the normalized maximum static friction force, \( F_\text{c} (t_\text{w})/F_\text{c} (I_\text{c}^\text{M}) \). We measured two different types of behaviour in the \( B-T \) phase diagram. When the temperature was close to the glass transition temperature, \( T_G \) [26], \( F_\text{c} (t_\text{w}) \) depended logarithmically on \( t_\text{w} \) as is shown in figure 2(a). Typical values for the slope of the curve are \( 7 \times 10^{-3} \text{s}^{-1} \). On the other hand, with further decreasing temperature, \( F_\text{c} (t_\text{w}) \) showed a rapid change for short \( t_\text{w} \)s (figure 2(b)). In other words, a characteristic timescale, \( t_\text{w}^* \) (typically 0.1 s at \( B = 0.5 \text{T} \) and \( T = 25 \text{K} \) in #R1), showed up for the change of critical current at low temperatures.

For the results obtained above, we first argue the results in the high-temperature region. In the thermally assisted flux flow (TAFF) [27–29], the spatio-temporal profile of vortices in the TAFF region can be described by a linear diffusion equation [11]. By solving this, it turned out that there is a characteristic timescale \( \tau \sim a_0^2/D \), where \( a_0 \) is the intervortex distance (\( \sim 50 \text{ nm} \)) and \( D \) is the diffusion coefficient of vortices. If we take \( D \sim 10^{-10} \text{m}^2 \text{s}^{-1} \) [30], we obtain \( \tau \sim 10^{-5} \text{s} \). Therefore, we expect that fast relaxation almost ceases for a much longer \( t_\text{w} \) than the above estimated \( \tau \). As a result, only very slow relaxation takes place for a longer \( t_\text{w} \). However, we do not understand the reason for the logarithmic dependence.

Next, we argue the results in the lower-temperature region, where the strong \( t_\text{w} \) dependence appeared below \( t_\text{w}^* \). First of all, it should be noted that the observed \( t_\text{w}^* \) is much larger (four orders of magnitude) than \( \tau \) estimated in the high-temperature TAFF region. It is almost impossible to explain such a huge difference after only a 2 K temperature change (27 and 25 K at \( B = 0.5 \text{T} \) in #R1) in terms of the temperature dependence of the diffusion coefficient. We can also consider the energy loss by the viscous motion of a single vortex during \( t_\text{w}^* \) over distance \( l \). This should be equal to the depinning energy, such as \( \eta \frac{1}{2} I^2 = j_\text{c} \Phi_0 \xi \), where \( \xi \) is the GL coherence length. When we put \( t_\text{w}^* = 0.1 \text{s} \), \( \eta = 5 \times 10^{-8} \text{N s m}^{-2} \) [31], \( j_\text{c} = 1.75 \times 10^7 \text{A cm}^{-2} \), and \( \xi = 20 \text{Å} \), we obtain \( l = 12 \mu \text{m} \). This is much larger than \( a_0 (\sim 50 \text{ nm}) \). It is unlikely that a single vortex can move over such a huge distance (\( l \gg a_0 \)) without being pinned by the pinning centre.

It is generally established that the interaction between the vortices becomes stronger at low temperatures, and the vortex lattice stiffness increases, then many vortices move coherently as a bundle [32, 27−29]. In the case of the relaxation of vortex bundle, the above formula should be modified as \( N \eta \frac{1}{2} I^2 = j_\text{c} \Phi_0 \xi l \), where \( N \) is the number of vortices in a bundle. For \( l \sim a_0 \), \( N \sim 6 \times 10^4 \) and the radius of the vortex bundle is about 12 \( \mu \text{m} \). Thus, it is very likely that large vortex bundles relax in a coherent manner. The above estimate demonstrates that the correlation length of moving vortices becomes much
Figure 2. The waiting-time dependence of the normalized maximum static friction force, \( F_s(t_w)/F_s(t_w^*) \), of (a) and (b) samples with a rectangular-type structure and (c)–(f) samples with a bridge-type structure. The lines in (a) and (b) are the fitting curve using \( F_s(t_w) \propto \ln t_w + \text{const.} \) and equation (2), respectively. The closed symbols are the data at \( B = 0.5 \) T, and the open symbols are the data at \( B = 1.0 \) T. The thick lines in (c) and (e) are guides to the eye.

For the thin films with a bridge-type structure (#B1 and #B2), the logarithmic \( F_s(t_w) \) is also observed close to \( T_g \) (figures 2(c) and (e)), which indicates that the creep motion dominates the dynamics of the vortices. On the other hand, any relaxation cannot be observed in both samples at lower temperatures (figures 2(d) and (f)). The same feature was also found in #B3 (not shown in the figure). This effect was not observed in the rectangular-type samples, suggesting that this is due to the enhanced surface pinning at the edge of a sample. The size of the vortex bundle increases with decreasing temperature. When the size of the coherently moving vortex bundles becomes comparable to the size of the bridge region in larger than the static correlation length. Such a long correlation length for a moving vortex was also observed in the noise measurement of the bulk single crystal of Bi2Sr2CaCu2Oy [23]. To be quantitative, using the collective creep theory, the data in figure 2(b) can be fitted by the following function [33],

\[
F_s(t_w) = F_s^* \left(1 - \frac{1}{1 + \frac{t_w}{t_w^*} \ln(1 + t_w/t_w^*)}\right),
\]

(1)

Therefore, the relaxation observed at low temperatures suggests that the relaxation of a large vortex bundle did take place at lower temperatures.
a sample, the vortex bundles are effectively pinned by the edge of a sample [34], which hinders relaxation from taking place. We have not considered the spatial distribution of the magnetic flux density explicitly, which has been discussed in terms of the critical state model, typically. However, even if it is taken into account, the essential features of the explanation presented above do not change. These will be discussed in the separate publication [35].

Moreover, we found that the boundary between the no-relaxation region and the logarithmic-relaxation region depends on the bridge size (the bridge width times the distance between Au electrodes). Figure 3(a) shows the ‘phase diagram’ of the relaxation phenomena, in the reduced temperature ($t = T/T_s$) versus the bridge size ($w d$) plane. The boundary between the no-relaxation region (closed symbols) and the logarithmic-relaxation region (open symbols) is not vertical. The thick line ($\propto (1 - t)^2$) is a guide to the eye, which indicates that the smaller the bridge size becomes, up to the higher temperatures the relaxation does not take place.

Finally, we discuss the result on the bridge-type sample with columnar defects (#C1). For the heavy-ion irradiated sample, the drastic change for the relaxation was observed. In this case, any relaxation cannot be observed in the $B - T$ phase diagram (figure 3(b)). This is because vortices are trapped at the columnar defects.

We can interpret the above transient dynamics of the driven vortices in terms of the physics of friction. The logarithmic waiting-time dependence in the samples with a rectangular-type structure close to $T_s$ (figure 2(a)), can be also seen in the friction at the solid–solid interface [6]. The increment of the real contact area during the waiting time is explained by the logarithmic waiting-time dependence of the maximum static friction force at the solid–solid interface. This transient relaxation mechanism is phenomenologically similar to the thermal creep motion of the vortices. During the waiting time, the vortices move and change their pinning configuration toward a more stable one energetically by the thermal-fluctuation force. Therefore, we can conclude that the essential physics of the vortices at a temperature close to $T_s$ is the same as that of logarithmic relaxation at the solid–solid interface. In other words, non-AC type friction ($F_r(t_w)$ is not constant) is realized in the vortex system at temperatures close to $T_s$. In general, in solid–solid friction, the waiting-time dependence of the static friction takes place since the interacting atoms prefer more stable positions among many metastable minima, and move to such positions with the aid of thermal fluctuation. Therefore, the small number of degrees of freedom under the presence of the small thermal fluctuation leads to less frequent relaxation, since the role of the thermal fluctuation becomes less effective. This mechanism is common to both vortices and solid–solid friction. Thus, our results at low temperatures (figures 2(b), (d), and (f)) in the vortex system can be also understood as relaxation phenomena with a small number of degrees of freedom, and the same mechanism can be also applied to solid–solid friction.

It is interesting that equation (1) reminds us of $F_r(t_w)$ of the boundary lubricated friction, where there exists a very thin layer (two or three atomic layers) of glassy contamination material at the interface. There the ageing effect is described well by the following formula [1],

$$F_r(t_w) = A + \frac{B\theta_0}{\theta_0 + (1 - \theta_0)\exp[-(t_w/t_{w*})^\beta]}$$

(2)

where $A, B, \theta_0$ and $\beta$ are parameters, and $t_{w*}$ gives the timescale with which the contamination material ‘solidifies’ by the thermal re-distribution of molecules. The data in figure 2(b) could also be fitted well by equation (2). It should be noted that the $t_w$ dependence of equation (2) contains the stretched exponential form as the essential part, which is commonly observed in the relaxation of glassy systems. Thus, these results suggest the importance of the relaxation of glassy movable objects at low temperatures, because the interaction force between the vortices rapidly increases with decreasing temperature. For the samples with a bridge-type structure, we can say that the behaviour in the smaller sample looks like AC type friction in the sense that no relaxation takes place. Therefore, it can be considered that one of the key components of the AC law is the sample size from figure 3(a). The AC type friction ($F_r(t_w) \sim \text{const.}$) is realized in the sample with columnar defects. Together with the size effect of the bridge-type samples, we can conclude that the strong pinning centre leads to the AC type friction.
Based on these results, we try to deduce the criteria for the validity of the AC law. The above results suggest that the pinning force, the thermal fluctuation, the size of coherently moving objects and the sample size all play crucial roles. In short, the strong interaction force at the interface and the small degrees of freedom of the moving object are key aspects for the validity of the AC law. These are drawn in a schematic figure, figure 3(c). This is consistent with our previous results on kinetic friction [12], where $F_{k}(v)$ is less velocity dependent with stronger pinning centres. Therefore, there must be a universal parameter which discriminates the AC type friction from the all other types of real friction. Based on the results presented above, we believe that the parameter $R$, such as $R = \alpha R_{c} \exp[-U_{0}/k_{B}T_{\text{eff}}]$, can be a candidate for such a universal parameter, where $\alpha$ is a proportional constant, $R_{c}$ is the radius of the coherently moving vortex bundle, $U_{0}$ is the activation energy which vortices have to overcome to move to more stable position among metastable minima, and $T_{\text{eff}} = T/N$ is the effective temperature ($N$ is the number of coupled degrees of freedom in one domain). The detailed expression for $T_{\text{eff}}$ depends on how strong degrees of freedom are coupled to each other. For instance, in the vortex system, $N$ is the number of vortices in the vortex bundle, when the vortices are coupled with each other completely. The essential point is that, if $R$ is comparable to the size of the sample, $L$, the pinning by the surface (or the boundary) becomes essential and the relaxation phenomena rarely take place. On the other hand, if $R$ is much smaller than $L$, we expect that the effect of the surface pinning can be ignored, and the vortices can relax into more stable position. In our experiment, $L$ corresponds to the working area for driven vortices, which is the product of $w$, $d$, and the film thickness. Since we used films (fixed to 3000 Å thickness) thinner than $R$, we can regard $L$ as an effective radius of the bridge size, $\sqrt{wd}/2$. It is very difficult to estimate reliable numbers for $R_{c}$ and $U_{0}$ based on our experimental result presented so far, because $U_{0}$ is related to the critical current density indirectly, and strongly depends on the temperature and history. $R_{c}$ also depends on various parameters such as the temperature, the magnetic field, the pinning potential, etc. Therefore, we must use very complex expressions in order to determine $R_{c}$ and $U_{0}$. (For example, see equations (4.19) and (4.21) for $R_{c}$, and equation (2.51b) for $U_{0}$ in Blatter et al [11].) In addition, because we cannot find a detailed expression of $\alpha$ and $T_{\text{eff}}$ at present, we need additional and more systematic experiments for the reliable estimation of these parameters. Here, we tentatively present possible numerical numbers in our sample based on the bridge size dependence depicted in figure 3(a). For sample #R1, we estimated the radius of the vortex bundle as $R_{c} \sim 12$ μm (at 25 K, 0.5 T). Since $T_{c}$ and $x$ for sample #B1 are almost the same as those for #R1, we consider that $R_{c}$ in #B1 (at 25 K, 0.5 T) is also $\sim 12$ μm. From an experiment of the time dependence of the magnetization, $U_{0}$ is estimated $\sim 50$ meV [36]. However, $U_{0}$ in our experiment should be much smaller than 50 meV, because we are discussing vortex relaxation among the metastable minima. Therefore, we assume that $U_{0} = 2$ meV and $T_{\text{eff}} = 1$ K ($T/25$). Since $\sqrt{wd}/2 = 12$ μm for #B1, we can get $\alpha \sim 7.4$ under the condition that $R \cong L(=\sqrt{wd}/2)$, where we expect that the effect of the surface pinning must be considered.

For the future issue, an understanding of the more detailed picture of the process during the waiting time (such as the distinction of the adhesion and the friction) will be also important. For example, Zhang et al [37] suggested from the computer simulation that the adhesion and the static friction are not directly related to each other. At present, we cannot clarify which process our experimental data contribute. As we wrote in the introduction, the effect of the vertical load is only ‘indirectly’ included in the interaction force between the driven vortices and pinning centres, whereas the strict definition for the vertical load is essentially important for the distinction between the adhesion and the friction. Since the essential feature in our simple approach is to focus on the common aspects among a large variety of phenomena and concepts which are apparently different from each other, we think that it is not always possible (or even not crucial) to associate all the details of the vortex physics with the physics of friction one to one. In relation to the above discussed issue, as we wrote in the very beginning, the AC law also describes that the friction is proportional to the normal load. However, it is not yet clear that this part of the law is understood by the same physics as the other parts of the AC law, which we discussed in this paper. Indeed, the dependence on the load is partly understood in terms of the increase of the true contact area [3]. It is a future issue whether or not the driven vortex system is also effective to understand this part of the AC law.

4. Conclusion

In conclusion, the transient response of the driven vortices was measured in La2-xSrxCuO4 thin films with different structures and pinning forces, and discussed both in terms of the vortex dynamics and the physics of friction. Using the obtained results, we proposed a universal parameter which discriminates AC type friction from all other types of real friction.

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