Study of friction using driven vortices of superconductor as a model system

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Abstract. Dynamics of driven vortices in high-\(T_c\) superconductors was investigated in terms of the elementary process of the motion and the microscopic friction. The \(I-V\) characteristics and the transient response of driven vortices were measured in \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\) thin films and in \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y\) bulk crystals. First, with an aid of a recently proposed scaling relation between the driving force and the velocity, we found that the non-Arrhenius process did exist for interacting vortices at low temperatures. With increasing magnetic field, Arrhenius process revived suddenly at the vortex-glass vs Bragg-glass transition, which shows that this approach is suitable as a new method to investigate the equilibrium phase diagram of vortices. After constructing an explicit formula connecting the motion of driven vortices to the physics of friction, the dependence of the kinetic friction force on the sliding velocity was investigated. Based on the experimental results, we propose that the non-Amontons-Coulomb behavior is regarded as the consequence of the broadened dynamic phase transition. We also found the remarkable dependence of the maximum static friction force on the waiting time at low temperatures. Such a strong dependence changed into a weak logarithmic dependence at higher temperatures. The strong time dependence suggests that a characteristic time scale to stabilize vortices exists at low temperatures. This relaxation phenomenon is very similar to the so-called boundary lubrication. These results imply that the dynamics of vortices can be used for a model not only of the dry friction but also of the lubricated friction.

1. Introduction
Control of friction is one of the most important key technologies in microscopic movable systems. However, the microscopic origin of friction has been a puzzle for over 500 years since Leonardo da Vinci’s pioneering studies on this topic. Empirically, the friction phenomena at the macroscopic interface are summarized as the Amontons-Coulomb law [1], which includes the fact that the kinetic friction is independent of the sliding velocity of the moving object, such as a massive block. This has been still the standard in most textbooks, and is successful in describing the friction for many systems, but it fails for others which have a kinetic friction force, \(F_k\), that changes from its static maximum value, \(F_s\), and depends strongly on the velocity, \(v\). Another interesting aspect of the friction is that \(F_s\) shows the aging effect [1]. For instance, when the driving force is applied periodically, \(F_s\) depends on the time of the intermission for the driving force. More surprisingly, a scaling relation has been proposed between the time dependence of \(F_s\) and the velocity dependence of \(F_k\) in thick papers [2]. Understanding all of these phenomena comprehensively by a minimal simple picture is a challenge for all physicists.
Figure 1. Schematic illustration of the potential well for a vortex. (a) zero driving force, where the right going probability and the left going probability is equal. (b) for a finite driving force, where the net flow becomes available. $\Delta U$ represents a net difference of the barrier height.

Recent progress in atomic force microscopy and surface force probes, together with large-scale computer simulations, is advancing our understanding of the origin of friction at the molecular and atomic scales (see, e.g., refs. [1, 3, 4] and references cited therein). However, it is still far from thorough understanding. This is probably because of the wear which is unavoidable in the experiments of the friction phenomena. Thus, we need convenient model systems, with which repetitive experiments are possible in a reproducible manner. From this viewpoint, we pay attention to the collective motion of electrons (or associated items) in the quantum condensate of solids. Two representative examples are the charge-densitywaves (CDWs) in quasi-one dimensional materials [5] and the quantized magnetic vortex lattice in superconductors under finite magnetic fields [6]. Indeed, the equation of motion for these collective condensates is very similar to that for the friction of massive block at the solid interface, suggesting that these systems are promising as good convenient model systems for physics of friction. In particular, we will focus on the dynamics of driven vortices in superconductors.

The dynamics of driven vortices has attracted much attention for a long time. In particular, since the discovery of high-$T_c$ cuprate superconductors [7], this issue has been studied very extensively both theoretically and experimentally [8]. One important viewpoint is the elementary process of the vortex motion. For large driving force, vortices move rather uniformly, with a periodic modulation of velocity suffered from the pinning centers (washboard oscillation). This washboard oscillation of driven vortices was observed experimentally [9, 10, 11]. On the other hand, close to the critical driving force (critical current density, $j_c$), vortices show a linear resistivity at finite temperatures [12]. This is called as flux creep, which is caused by the linear decrease of the potential barrier as a function of driving force (figure 1). This thermally activated motion with the linear decrease of the potential barrier has been a starting point of all the analysis for a long time. However, it is not obvious whether this thermally activated behavior proportional to $\exp(-\Delta U/k_BT)$ (below we call this behavior the Arrhenius behavior, $k_B$ is the Boltzmann constant, $T$ is the temperature, and $\Delta U$ is the net difference of the barrier energy) is also valid for interacting vortices. Recently, a non-Arrhenius behavior was proposed
based on a numerical simulation [13]. They proposed a new scaling relation as

\[ v(T, F) = T^{1/\delta} S(T^{-1/\beta \delta} f), \]  

(1)

where \( f \equiv 1 - F_c/F \), \( F \) and \( F_c \) are the driving force and the critical driving force, respectively, \( v \) and \( T \) are the velocity of the vortex and the temperature, respectively, and \( \beta \) and \( \delta \) are the dynamic critical exponents, and \( S \) is the scaling function. It was found that the so-called \( \beta \delta = 1.5 \) in the Bragg-glass phase [14], whereas \( \beta \delta = 1.0 \) in the so-called vortex-glass phase [14]. This suggests that the non-Arrhenius behavior does exist in the Bragg-glass phase, which should be checked in experiments.

The other important viewpoint is the dynamic phase diagram of driven vortices [8]. It is a very interesting subject what kind of phase diagram is available in the magnetic-field vs temperature vs driving-force space [15, 16, 17, 18, 19, 20, 21, 22, 23]. Even restricting our interest on the moving state, various styles of motion have been proposed, indeed, for driven vortices, such as plastic motion [19], moving Bragg glass [17], and smectic motion [16]. We investigated the noise generated by the vortex motion by measuring the local density noise [24, 25] and the velocity noise [11] simultaneously [26]. Together with the resistivity data and the ac-dc interference data, we found that the vortices first showed the plastic flow. With increasing driving force, it changes into the moving Bragg glass, less coherent state, and finally, into the moving “liquid” state [26].

Once the dynamics of driven vortices is becoming understood, the next-step concern is an explicit link between the dynamics of driven vortices and the physics of friction. In the next section, we will briefly summarize the procedure of how to extract the static and kinetic friction from the quantities shown up in the physics of driven vortices. Based on this, we will discuss the kinetic friction as a function of velocity and the static friction as a function of waiting time.

2. Relation between the driven vortices and physics of friction

To find out an explicit relation between the friction and the parameters shown up in the experiment of driven vortices, a theoretical formulation of the solid-solid friction at the interface by Matsukawa and Fukuyama is helpful [27]. According to them, the friction is the summation of the interatomic interaction at the interface. If it is seen from the movable object, it can be regarded as the pinning force suffered from the other object. Furthermore, in the steady state, this is equal to the external driving force. However, it should be noted that the average viscous force should be subtracted from the external force, since the friction is the energy dissipation from a representative degree of freedom to others. This is understood physically as follows. If a driven block slides on a rough surface, the resistive force on the block has two components: one due to the interaction with the substrate (standard kinetic friction \( F_k \)) and an additional (hydrodynamical) resistance if the driven block is submerged in a fluid (e.g., molasses). Similarly to a massive sliding block in molasses, when a vortex moves inside a superconductor, it experiences a resistive force because of the surrounding superfluid interacting with the vortex core. This dissipative flux flow exists even when the sample has zero pinning impurities. This is the reason why the average viscous force should be subtracted. Thus, the kinetic friction, \( F_k \), for driven vortices is represented as

\[ F_k = j \Phi_0 - \eta v = j \Phi_0 (1 - \frac{\rho}{\rho_\infty}), \]  

(2)

where \( \Phi_0 \) is the flux quantum, \( j \) is the current density, \( \eta \) is the viscosity, \( \rho \) and \( \rho_\infty \) are the resistivity and the flux flow resistivity, respectively, and \( F_k \) is the kinetic friction per unit length of a single vortex [28, 29, 30]. We can know both \( j \) and \( \rho \) by the usual dc I-V characteristics measurement, whereas \( \rho_\infty \) can be obtained in the microwave complex surface-impedance measurement [31, 32].
The above mentioned consideration is for the so-called dry friction. In addition to the dry friction, the sliding friction under the existence of a liquid lubricant at the interface is also important for an industrial application. There are different regimes distinguished by the thickness of the lubricant. When it is thick, the elastohydrodynamics (EHD) of the lubricant mainly contributes to the friction, which is called as the EHD regime. On the other hand, if the lubricant layer is very thin, the molecular characteristics of the lubricant turns out to be essential, and it exhibits peculiar dynamics such as the solidification of the lubricant. This regime is called as the boundary lubrication (BL) regime, whose understanding is essential for the construction of micrometer- or nanometer-scale machines. Below we will show that both the BL and the EHD regimes can be also treated in our model approach.

3. Experiments

Single crystals of Bi$_2$Sr$_2$CaCu$_2$O$_y$ (BSCCO) and La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) with $x=0.14$ used in this study were made by ourselves using the floating zone method. Superconducting transition temperatures, $T_c$’s, were 90 K (BSCCO) and 37 K (LSCO), respectively, and the typical dimension of the sample was $0.5 \times 1 \times 0.05$ mm$^3$. Single crystalline films of LSCO were prepared on the LaSrAlO$_4$ (LSAO) substrate by the pulsed laser deposition, using the polycrystalline targets.

In dc $I-V$ characteristics measurement, Joule heating becomes serious at high current densities. Thus, $I-V$ characteristics measurement using short rectangular pulses was also performed, details of which were described elsewhere [30].

For obtaining the flux-flow resistivity, $\rho_\infty$, we need both the real and the imaginary parts of the microwave surface impedance, because of the large pinning frequency of high-$T_c$ superconductors. With an aid of a general phenomenological model [33], we can extract flux-flow resistivity. Details on the procedure were described in the literatures [31, 32, 34].

Furthermore, we applied a sawtooth-like pulsed current to obtain the transient response of the vortices. By comparing the critical current densities for different waiting times, we obtained the waiting-time dependence of $F_s$, $F_s(t_w)$, in the dynamics of vortices [35]. Empirically, heating effect is almost negligible below 0.5 W. In our measurements the maximum power generated in the sample was about 1 $\mu$W. Thus, we safely conclude that the obtained $F_s(t_w)$ was not caused by the Joule heating effect.

4. Results and discussion

4.1. Driven vortices near the critical driving force

Figure 2 shows the typical $I-V$ characteristics of an LSCO film with $x=0.14$ at low temperatures for $B = 0.5$ T, where we can identify the critical current, $I_c$, rather easily. We analyzed the data in terms of the scaling relation, equation (1). To do this, we first determined $\beta$ by fitting the lowest-temperature (5 K) $I-V$ data to $\Delta V \propto (I-I_c)^\beta$ ($\Delta V$ is the extra voltage generated above $I_c$), and found that $\beta=0.681$. Using this number, next the $I-V$ data are plotted in $vT^{-1/\delta} \sim T^{-1/\beta \delta} (1 - F_s/F_c)$, as is shown in figure 3. In figure 3, we tried for three different $\beta \delta$ numbers. This shows that $\beta \delta=1.5$ gives the best fit, which agrees well with the Bragg-glass case of the simulation, and supports the existence of the non-Arrhenius process in the vortex motion.

Figure 4 is the same plot for the data at $B =2.0$ T. Different from the data at 0.5 T, $\beta \delta =1.0$ gives a better fit, which corresponds to the Arrhenius behavior.

We also plotted the $\beta$ value as a function of magnetic field in figure 5. $\beta$ changes suddenly between 0.5 T and 1.0 T, suggesting a phase transition from the Bragg glass to the vortex glass exists between these magnetic fields. Indeed, the transition between the Bragg glass to the vortex glass in LSCO was also suggested in $\mu$–SR [36] and neutron diffraction [37] experiments. It should be noted that $\beta$ values below 0.5 T agree well with the theoretical prediction for the Bragg-glass phase, whereas those above 1.0 T do not agree with the prediction for the
Figure 2. $I − V$ characteristics of an LSCO film with $x = 0.14$ at $B = 0.5$ T. The inset shows the expanded plot near $j_c$.

Figure 3. The scaling plot of the $I − V$ data shown in figure 2 for different $\beta\delta$ values. (a) 1.0, (b) 1.5, (c) 2.0.

vortex glass. We speculate that the $\beta$ value for the vortex-glass phase strongly depends on the explicit form of the interaction between the vortex and the pinning centers. We believe that the incorporation of a different type of the potential from that in ref. [13] leads to a different $\beta$ value. Thus, we do not think that the disagreement of the $\beta$ value between our experimental result and the theory is serious. Rather, these results suggest that the technique using the scaling behavior of the $I − V$ characteristics discussed above is a new good tool to investigate the phase diagram of vortices.

4.2. Friction of vortices
4.2.1. kinetic friction of vortices
Previously, we investigated the $I − V$ characteristics and the flux flow of vortices in LSCO, and discussed the kinetic friction of vortices as a function of
Figure 4. The scaling plot of the $I - V$ data at $B = 2$ T for different $\beta\delta$ values. (a) 1.0, (b) 1.5.

Figure 5. Magnetic field dependence of $\beta$. Thick solid lines are the numbers predicted by Luo and Hu[13], for the Bragg glass and the vortex glass, respectively.
velocity, utilizing equation (2) [29]. First, we show that the behaviors reported in ref. [29] are restricted neither in a special material nor in the film sample. Figure 6 shows the kinetic friction, $F_k$, of the other high-$T_c$ cuprate superconductor, BSCCO, as a function of the vortex velocity, $v$, at various temperatures for 100 G and 200 G. The data show essentially the same behavior as was observed in the LSCO films [29]. Namely, $F_k$ increases with increasing $v$, showing a broad maximum around at some velocity of hundreds m·s$^{-1}$, and decreases with further increasing velocity. At higher temperatures and higher magnetic fields, the material shows a smaller $F_k$.

In particular, it is noteworthy that the data at 50 K are rather close to the Amontons-Coulomb behavior. If the measurement of $F_k(v)$ at much lower temperatures becomes possible, we believe that it shows the Amontons-Coulomb-like behavior. These data were taken in a bulk sample. Thus, these suggest that the above mentioned behavior is observed not only in a specified material, but is rather generic to driven vortices of superconductors.

The significance of these results in terms of the physics of friction is as follows. Considering the motion of a massive block in macroscopic scale, near the threshold for the onset of motion, a driven block accelerates and stops showing “stick-slip” motion, which plays a central role in geology, tribology, and many industrial processes [4, 38]. This stick-slip motion can be viewed as strong fluctuations near the sharp transition [39] between two states having static friction, $F_s$, and kinetic friction, $F_k$. Experiments (e.g., refs. [40, 41]) support this fluctuation mechanism and pose the question of why in some cases $F_s > F_k$, while in other cases $F_k > F_s$. Our previous comparative study in pristine and irradiated samples showed the existence of the crossing point in the $F_k(v)$ data between pristine and irradiated samples [29], which can be regarded as the transition from the $F_s > F_k$-regime to the opposite regime, $F_k > F_s$. Thus, the behaviors shown above suggest the following model for the velocity dependence of $F_k$ (figure 7). For a macroscopic system where the thermal fluctuation is not effective, there is a sharp transition from a static state with $F_s$ to a sliding state with $F_k$. When the effective system size decreases

Figure 6. $F_k$ as a function of velocity in a BSCCO bulk sample for 100 G (open marks without crosses) and 200 G (open marks with crosses inside).
by changing some parameters such as temperature, magnetic field, etc., thermal fluctuation plays a more important role, which broaden the sharp phase transition for the macroscopic system. Thus, the observed $F_k(v)$ can be regarded as the broadened dynamic phase transition. From this viewpoint, the observed behavior can be summarized as follows. These results (1) provide a link between microscopic friction of vortices and macroscopic-scale friction; (2) explain the roundness of the static-kinetic friction transition in terms of system sizes (critical-phenomena view) and thermal fluctuations; and (3) explain the crossing of the kinetic friction $F_k$ versus velocity $v$ for our pristine (high density of very weak defects) and our irradiated samples (with lower density of stronger pinning).

4.2.2. Static friction of vortices [35]

A challenge on static friction is to understand the aging effect of the maximum static friction force, $F_s$, on the waiting time, $t_w$, which is the intermission time of a repetitively applied driving force. This $F_s(t_w)$ has been investigated for the dry friction [42], the lubricated friction [43], the agar gel [44], and the charge density wave [45]. Previously, studying the relationship between $F_s(t_w)$ and $F_k(v)$ in a high-$T_c$ superconductor La_{1.85}Sr_{0.15}CuO_4, we showed that the driven-vortex system exhibited a non-Amontons-Coulomb behavior owing to the existence of a large thermal fluctuation [30].

We further investigated $F_s(t_w)$ for different pinning forces, and found two different kinds of $F_s(t_w)$. Near the field-dependent vortex glass-liquid transition temperature, $T_g(H)$, $F_s$ depends on $t_w$ very weakly, which is represented as

$$F_s(t_w) = A + B \log t_w \quad (A, B: \text{constants}).$$

On the other hand, a characteristic time scale, $\tau$, appears at lower temperatures. Below this time scale, $F_s(t_w)$ becomes prominent. We note that this strong dependence can be fitted by a model equation for the boundary lubrication (BL) regime. In the BL, because of the thermal redistribution and the solidification of the lubricant film, $F_s(t_w)$ obeys the following empirical equation [46],

$$F_s(t_w) = A + \frac{B \theta_0}{\theta_0 + (1 - \theta_0) \exp(-t_w/\tau^\beta)}.$$

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**Figure 7.** A schematic illustration of the $F_k$ as a function of velocity, in terms of the dynamic phase transition picture. Different curves correspond to the ones for different parameters. $Q$, $l$, $\eta$, and $F_d$ represent height of the potential barrier, the period of potential, viscosity, and driving force, respectively.
where $\beta = 1$ in ref. [46], and $\theta_0$ is the order parameter denoting the state of the lubricant film. $\theta_0 = 0$ means a solid state, whereas $\theta_0 = 1$ means a liquid state. We found that the data which depended on $t_w$ strongly were fitted by equation (3) very well, and obtained the fitting parameters of $\theta_0 = 0.93 \sim 0.99$ and $\tau = 0.5$ ms$^{-1}$-$15$ ms, and $\beta = 0.5$. Large numbers of $\theta_0$ mean that the thermal fluctuation is fairly large in the vortex system, which is consistent with our previous conclusion[29]. Thus, this suggests that the lubricated friction can be also described by the dynamics of vortices. On the other hand, the very weak $t_w$ dependence of $F_s$ near $T_g(H)$ can be regarded as a phenomenon in the EHD regime, because there is no characteristic time scale for the solidification of the lubricant when the lubricant film is thick. To sum up, we can obtain various different models of the friction for the different thickness of the lubricant by changing parameters such as temperature, magnetic field, etc.

5. Conclusion
Dynamics of driven vortices in high-$T_c$ superconductors was investigated in terms of the elementary process of the motion and the microscopic friction. The $I$-$V$ characteristics and the transient response of driven vortices were measured in La$_{2-x}$Sr$_x$CuO$_4$ thin films and in Bi$_2$Sr$_2$CaCu$_2$O$_y$ bulk crystals. First, with an aid of a recently proposed scaling relation, we found that the non-Arrhenius process does exist for interacting vortices at low temperatures. With increasing magnetic field, Arrhenius motion revived suddenly at the Bragg-glass vs vortex-glass transition, which shows that this approach is suitable as a new method to investigate the equilibrium phase diagram of vortices. After constructing an explicit formula connecting the dynamics of driven vortices to the physics of friction, the dependence of the kinetic friction force on the sliding velocity was investigated. Based on the experimental results, we proposed that the non-Amontons-Coulomb behavior was regarded as the broadened dynamic phase transition. We also found the remarkable dependence of the maximum static friction force on the waiting time at low temperatures. The result suggests that the existence of a characteristic time scale to stabilize vortices at low temperatures. This relaxation phenomenon is very similar to the boundary lubrication. Such a strong dependence changed into a weak logarithmic dependence at higher temperatures. These results imply that the dynamics of vortices can be used for the model not only of the dry friction but also of the lubricated friction.

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