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# Effect of surface grooves on kinetic friction of a rubber slider

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ABSTRACT

This study discusses the effect on kinetic friction of the number of surface grooves present on the contact surface of a rubber slider. From some experiments, it was found that the number of grooves is important in determining the kinetic friction. For a dry interface, kinetic friction decreases as the number of grooves increases. However, for a wet interface, the effect of the grooves on kinetic friction depends on the surface roughness of the rubber slider. For a rubber slider with a relatively rough surface, kinetic friction increases as the number of grooves increases. In contrast, for a smooth rubber slider and a wet interface, kinetic friction decreases with increasing number of grooves.



## 1. Introduction

Sliding surfaces of rubber-like material are widely used in many engineering applications. In the case of components for power transmission (e.g., tires, belts, shoe soles), a large and steady friction force is required to avoid unnecessary slippage. On the other hand, in some lubricated systems, low kinetic friction is needed to achieve low energy loss during sliding. In addition, to prevent friction-induced vibration such as stick–slip motion, the difference between static and kinetic friction should be controlled to a low value [1–3].

In order to obtain design criteria for rubber sliding systems, there have been a number of studies. As an engineering example, Yamaguchi et al. developed a novel design of shoe sole [4]. They found that a combination of rough and smooth surfaces is an effective design for determining the static and kinetic friction forces of a shoe sole under wet (lubricated) conditions. Further, Moriyasu et al. investigated optimizing the shape of a shoe sole for increased kinetic friction by focusing on bulk deformation of the sole [5]. On the other hand, from basic studies focusing on model experiments and numerical simulations of rubber friction, the macroscopic geometry of a rubber slider was found to be important in determining the static and kinetic friction forces. Gabriel discussed the influence of the surface geometry on kinetic friction [6]. Murarash demonstrated on the control of rubber friction focusing on the optimization of the surface geometry [7]. Capozza discussed on the effect of the loading configuration on the static friction force [8]. Greiner developed a textured surface that has a low adhesion and friction force [9]. Additionally, Capozza indicated that macroscopic surface grooves are theoretically effective in reducing static friction [10]. Maegawa et al. discussed the effect of friction-induced torque on kinetic friction force, focusing on bulk deformation of a rubber slider [11].

In the above researches, it was found that macroscopic deformations at a contact interface, characterized by the slider shape and the loading configuration, are important in determining friction for a slider of rubber-like material. The present study investigated kinetic friction forces for a rubber slider with macroscopic surface grooves under dry (non-lubricated) and wet (lubricated) conditions. In our experiments, the time dependence of tangential load between a silicon rubber slider with surface grooves and a smooth poly (methyl methacrylate) (PMMA) surface was monitored. The number of grooves and the surface roughness of the slider were treated as variable parameters. Consequently, it was found that kinetic friction under the dry condition decreases as the number of surface grooves increases, regardless of differences in surface roughness. In contrast, for the lubricated condition, the effect of groove number on kinetic friction strongly depends on the level of surface roughness. When a rubber slider with a relatively rough surface is used with a wet interface, kinetic friction increases as the groove number increases. In contrast, for a smooth rubber slider and a wet condition, kinetic friction decreases with increasing number of grooves.

## 2. Experimental details

### 2.1. Apparatus and procedure

Fig. 1 shows a schematic of the experimental setup used in this study; the system is nearly identical to one used previously [11].

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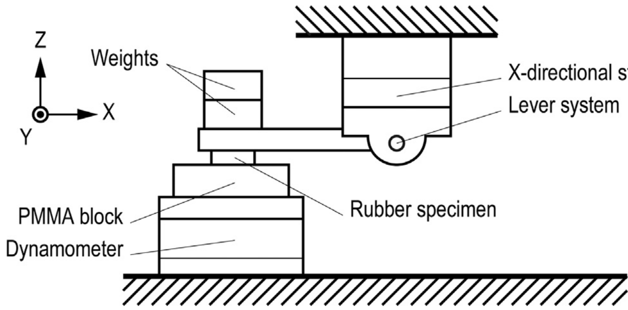


**Fig. 1.** Experimental setup.

However, as will be described below, the shape of the specimens differs. This system has a plane contact between a rubber slider with surface grooves and a smooth PMMA surface. A (normal) dead load is applied to the rubber slider by a lever system, and an *X*-directional motorized stage, which is mounted in the lever system, provides a sliding motion. A three-directional dynamometer is rigidly held under the PMMA plate.

In the dry (non-lubricated) condition, the rubber slider was set on the PMMA plate without lubricant with a dead normal load $F_Z$ of 30 N. In contrast, in the wet (lubricated) condition, a lubricant (mineral oil with a viscosity of 220 $mm^2/s$) was applied on the PMMA plate before positioning the slider. After a waiting time of 20 s, the slider was driven at constant sliding speeds *V* of 0.1, 0.5, 1.0, 5.0, or 10.0 mm/s in the positive *X* direction. During sliding motion, friction force between the bottom face of the rubber slider and the smooth PMMA plane was monitored using the three-directional dynamometer at a sampling rate of 10 kHz. It should be noted that in order to prevent the ingress of debris into the contact interface, their surfaces were cleaned up before the onset of the each experiment.

### 2.2. Specimens

Eight types of silicon rubber sliders (Shore A 70) were prepared. The other mechanical properties of the silicon rubber, tensile strength and tensile elongation, are 7.4 MPa and 300%, respectively. Fig. 2 illustrates the dimensions of the rubber specimen used in this study. It should be noted that the term "grooves" used in this paper means the macroscopic channel fabricated on the rubber surface, although this term is often used as a microscopic surface texture in many topics. The number of deeply-penetrating surface grooves *N* and the surface roughness $R_a$ of the rubber slider contact surface were varied as experimental parameters. Specimens with a rough surface ($R_a$=12.0 μm) are designated: *Rough_N0*, *Rough_N1*, *Rough_N3*, and *Rough_N7* for *N*=0, 1, 3, and 7, respectively. Similarly, specimens with a relatively smooth surface ($R_a$=0.15 μm) are designated: *Smooth_N0*, *Smooth_N1*, *Smooth_N3*, and *Smooth_N7*. It should be noted that the total areas of the apparent contact region $A_{atot}$ were identical, i.e., 200 $mm^2$, for all specimens.

## 3. Experimental results

### 3.1. Time dependence of tangential load

Fig. 3 shows the time dependence of tangential load $F_X$ for the rough specimens (i.e., *Rough_N0 — Rough_N7*) under dry and wet conditions. The origin of the time axis is the instant when the driving stage starts to move in the positive *X*-direction. For both conditions, $F_X$ gradually increases with time during the static friction regime and then reaches a steady value, which is defined as the kinetic friction force, $F_k$. The curves are labeled from the bottom upwards in increasing order of the kinetic friction value. In general, the magnitude of $F_k$ strongly depends on the type of specimen and the absence or presence of lubricant. It is clear that $F_k$ for the wet condition is smaller than for dry condition because a presence of lubricants (lubricant film) works to reduce the total area of the real solid contact regions.

Focusing on the case for the dry condition and rough specimens, it is found that $F_k$ decreases as the number of grooves *N* increases, although the total area of the apparent contact region $A_{atot}$ is identical for all specimens. It implies that the total area of real contact $A_{rtot}$ differs between specimens. In contrast, the effect of *N* on $F_k$ in the wet condition is opposite to that in the dry condition: with lubrication, $F_k$ increases with increasing *N*. However, the change in $F_k$ produced by the change in *N* is much smaller than that under the dry condition.

Fig. 4 shows the time dependence of the tangential load $F_X$ for the smooth specimens *Smooth_N0 - Smooth_N7* under dry and wet conditions. Comparing the dry kinetic friction $F_k$ indicated in the curves for the rough and smooth specimens, the same general trend is found: $F_k$ decreases as the number of grooves *N* increases. In contrast to the rough surface cases, the time dependence of the tangential load $F_X$ for the smooth surface with lubrication is quite different in its approach to attaining sliding or kinetic friction $F_k$. The initial slope (i.e., $t=0$) of the $F_X$ curves strongly depends on *N*. It is found that the magnitude of the slope increases with increasing *N*. Thus, a long sliding distance is needed to achieve higher values of the friction force $F_k$.

### 3.2. Effect of the number of grooves on kinetic friction

The effect of number of grooves *N* on the kinetic friction force $F_k$ is summarized in Fig. 5. Fig. 5(a) shows the effect of *N* on $F_k$ for the rough specimens, while Fig. 5(b) is for the smooth specimens. For the dry condition, the same general trend is seen for both rough and smooth specimens: $F_k$ decreases with increasing *N*. This implies that the mechanism determining the magnitude of $F_k$ applies regardless of the surface roughness. However, for the wet condition, the mechanism relating $F_k$ to *N* is more complex: for the rough specimens, $F_k$ increases with increasing *N*, while for the smooth specimens, $F_k$ decreases. The mechanism underlying these results will be discussed in the following sections.

## 4. Discussion

### 4.1. Dry condition

As described above, for both rough and smooth specimen types under the dry condition, $F_k$ decreases as *N* increases. When examined more closely, it is clear that $F_k$ decreases more slowly with increased *N* for the rough specimens than for the smooth. In order to explain this trend, the present study focused on the effect of friction-induced torque on the kinetic friction force, as developed by Maegawa et al. [11]. Those authors experimentally and theoretically demonstrated that kinetic friction of a rough rubber block sliding on a rigid smooth plane strongly depends on the shape of the slider. When a rubber block with a relatively small contact length and large height is used as a slider, the kinetic friction force has a relatively small value compared to that of a rubber block with a greater length and a smaller height, because in the former case, a large friction-induced torque works to reduce the total area of the real contact regions.

In that study [11], the area of real contact $A_r$ of a rectangular rubber slider, in which friction-induced torque acts on the contact interface, was estimated based on a simplified model using