Tribology International 102 (2016) 532–539

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

New insight into the mechanism of static friction: A theoretical prediction of the effect of loading history on static friction force based on the static friction model proposed by Lorenz and Persson

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ARTICLE INFO

Article history:
Received 5 September 2015
Received in revised form
14 April 2016
Accepted 17 April 2016
Available online 21 April 2016

Keywords:
Static friction
Frictional shear stress
Loading history
Elastomer

ABSTRACT

This study provides a new insight into the field of static friction. Based on the static friction model developed by Lorenz and Persson, in which it is assumed that a slip distance characterizes the level of frictional shear stress acting on the contact interface, we pointed out that tangential loading history is an important factor for determining the value of static friction. The stop-restart motion increased the level of static friction force, while the stop-inversion motion reduced the static friction.

1. Introduction

The mechanism of static friction has been an actively studied topic in the fields of tribology, geophysics, and mechanical engineering [1–3]. Following the pioneering experiments by Fineberg's group [4,5], in which temporal and spatial development of precursory local slip were observed in situ, a number of studies were performed to gain a complete understanding of the origin of static friction. As pointed out by David and Fineberg [6], "static friction is not a material constant", i.e., static friction depends on several system parameters: the stiffness properties of the contact interface [7–9]; the magnitude of normal load [10–12]; the loading configuration of the external forces; and the geometry of the sliding object [13–15]. These results indicate there are a number of methods for tuning static friction force. In mechanical engineering, it is important to fully optimize the system parameters listed above to improve the ability of sliding systems.

Based on a simplified static friction model, Lorenz and Persson derived a general rule in characterizing the level of static friction force [14]. They stated that the static friction force decreases due to the existence of different surface regions that begin to slip at different times during the external loading period. Thus, the initiation process of sequential precursory local slip that occurs prior to the onset of the global slip characterizes the level of static friction force. This consideration explains why static friction depends on the system parameters described above.

This study focused on the effect of tangential loading history on the magnitude of static friction. Based on the static friction model developed by Lorenz and Persson [14], we developed a theoretical prediction where the sequence of the external loading affects the magnitude of the static friction force. Sequences of external loadings used for this study were stop-restart and stop-inversion motions.

2. Static friction model by Lorenz and Persson

Lorenz and Persson [14] discussed how static friction depends on the elasticity and geometry of a sliding object using a simplified analysis based on a 1D slab model. The advantage to using this simplified model is that the analysis is effective in finding dominant factors for characterizing phenomena. Additionally, a simplified model allows a theoretical solution to be derived analytically.

In our study, we used the Lorenz and Persson model, as illustrated in Fig. 1, to discuss the effect of the loading history on static friction force. To facilitate the comparison between their results and results obtained in our paper, identical symbols were used. In this model the frictional shear stress τ_f acts on the contact

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http://dx.doi.org/10.1016/j.triboint.2016.04.021
0301-679X/

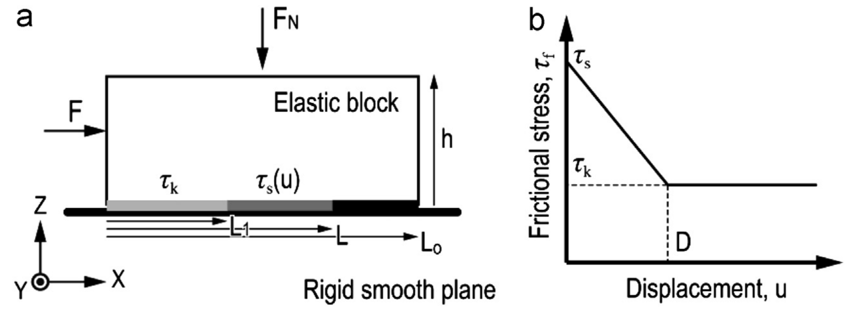

Fig. 1. Static friction model developed by Lorenz and Persson [14]. (a) A rectangular elastic block with a nominally flat surface slides on a rigid substrate. Normal and tangential loads F and F_N are applied at the side and top faces of the slider. (b) Frictional stress τ_f acts on the contact interface between the elastic block and substrate and depends on displacement u. When the displacement u is smaller than a characteristic distance D, $\tau_f=\tau_s-(\tau_s-\tau_k)\ u/D$. When u is larger than D, $\tau_f=\tau_k$.

interface between the elastic slider and the smooth surface of the rigid substrate. It is assumed τ_f decreases from τ_s to τ_k as the surface displacement u increases in the X direction, as shown in Fig. 1(b). When u is smaller than a characteristic distance D, $\tau_f=\tau_s-(\tau_s-\tau_k)\ u/D$. In contrast, when u is larger than D, $\tau_f=\tau_k$. Thus, the amount of the local slip D is needed to drop frictional stress from τ_s to τ_k. As discussed in the original paper by Lorenz and Persson [14], the amount of D is typically characterized by the time of interfacial relaxation process (aging), which ranges from nm to mm. For example, thermally activated creep or inter diffusion of polymer chains characterizes D as approximately 1 nm. On the other hand, in the case of plastic creep, D will be under the order of a few μm that is characterized by surface roughness, elastic modulus and the hardness of the contacting solids. In other cases, D is determined by a surface waviness, or structure in the order of a few mm. It should be noted that the local stress fluctuations resulting from the randomly distributed asperity contacts are averaged over large enough surface areas. Thus, the local distribution of shear and normal stresses are removed. The slider is made of an elastic material with Young's modulus E. The deformation of the elastic slider is modeled by a 1D model. In addition, any kinetic effects such as the fast propagation of a crack tip were not considered. The crack-like front (at $x=L$ in Fig. 1) was assumed to move adiabatically as the loading force increased. Here, it should be noted that L_0 is the slider length. L_1 and L are the lengths from the left edge of the slider to the front edge of the stick and slip regions where τ_s and τ_k act on the contact interface as shown in Fig. 1(a), respectively. Additionally, the width of slider in the Y direction is described as L_y, and h is the height of the slider in the Z direction, as illustrated in Fig. 1(a).

Lorenz and Persson derived the theoretical solution of the maximum value of the nominal (macroscopic) frictional shear stress τ_{max}. This maximum value corresponds to the frictional shear stress required to initiate global slip as follows:

$$\tau_{max}=\begin{cases}\tau_k-\frac{\tau_k}{\kappa L_0}\mathrm{acos}\left(\frac{\tau_k}{\tau_s}\right)+\frac{\tau_s}{\kappa L_0}\left[1-\left(\frac{\tau_k}{\tau_s}\right)^2\right]^{1/2} & \text{for } \kappa L_0>\mathrm{acos}\left(\frac{\tau_k}{\tau_s}\right)\\ \frac{\tau_s}{\kappa L_0}\sin(\kappa L_0) & \text{for } \kappa L_0<\mathrm{acos}\left(\frac{\tau_k}{\tau_s}\right)\\ \frac{\tau_s}{\kappa L_0}\left[1-\left(\frac{\tau_k}{\tau_s}\right)^2\right]^{1/2} & \text{for } \kappa L_0=\mathrm{acos}\left(\frac{\tau_k}{\tau_s}\right)\end{cases} \quad (1)$$

where,

$$\kappa=\left(\frac{\tau_s-\tau_k}{hED}\right)^{1/2} \quad (2)$$

From Eq. (1) it is clear that the maximum value of the nominal frictional shear stress τ_{max} is not a material constant. Here, it should be noted that the maximum static friction force F_{smax} is described as $\tau_{max}A$, where A is the area of the apparent contact region; that is, $F_{smax}=\tau_{max}A = \tau_{max}L_yL_0$. Thus, the Lorenz and Persson model provides a clear solution to the question of how static friction depends on the geometry of the slider, and the elastic properties of the slider. The details of the analysis, results and the methodology used to develop the solution are described in Lorenz and Persson's [14] original paper.

3. Two types of different loading history

Fig. 2 illustrates the two types of different loading sequences that are the focus of this study. Fig. 2(a) shows the basic configuration of the sliding model. As in the case of the Lorenz and Persson model, the normal and tangential loads F and F_N are applied on the top and side face of the slider. In our model, it is assumed that F is applied via a spring with a stiffness K. The left side of the spring moves in the X direction with a driving speed of V. In this analysis, the kinetic effects are not considered. Therefore, the value of K does not affect the conclusions obtained in this study.

The changes in driving speed V and nominal frictional shear stress τ of the stop-restart motion are schematically drawn in Fig. 2(b). As illustrated, the loading sequence is divided into three periods, i.e., first loading period, stopping period, and second loading period. In the first loading period, the left edge of the spring moves in the positive X direction at a constant speed of V_0. The nominal stress τ increases with time until τ reaches the maximum value τ_{max}, at which time slip occurs over the entire contact region, i.e., global slip. The value of τ_{max} corresponds to the maximum static friction force. Subsequently, τ decreases from τ_{max} to τ_k as the frictional phase changes from static friction to kinetic friction. The decrease in τ occurs instantaneously since this model does not account for kinetic effects such as crack tip propagation. In this study, it is assumed that during the total slip period, the sliding speed of the contacting surface of the slider is equal in all of the regions. Additionally, it is also assumed that the transition from the slip to re-static friction occurs when the sliding speed reaches zero. Therefore, the transition from the total slip to the total stick at each contact region occurs simultaneously at the moment of the onset of the stopping period, because during the stopping period, the increase in tangential load stopped as the motion of the spring stopped, i.e., $V=0$. Furthermore, it should be noted that during the stopping period, tangential and normal loads are continuously applied. In the stopping period, the applied tangential force is equal to the static friction force. Therefore, the internal strain during the total slip period is stored before and after the transition. After a certain waiting time, the increase in tangential loading restarts under a constant speed V_0. This study focused on the value of the maximum shear stress at the second loading period, i.e., τ_{max}'. As described in following sections, it is found that τ_{max}' is larger than τ_{max}. Thus, the existence of the