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Effect of track roughness generated micro-hysteresis on rubber friction in case of (apparently) smooth surfaces

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A B S T R A C T

In this study, the work of Mofidi et al., 2008 [6] is cited and the focus is put on the finding that the friction reported for lubricated apparently smooth surfaces (sealing applications) may be dominated by micro- or surface roughness generated hysteresis. Contrary to the very high coefficients of friction measured, Mofidi et al. did not analyze their test results and test configuration in depth and did not compare their results to experimental observations taken from the literature. In this study, the author makes an attempt to meet these needs and reanalyze/reinterpret the results of Mofidi et al.

1. Introduction

As it is well known different physical processes contribute to rubber friction. Dry friction of rubbers is controlled, among others, by adhesion, macro hysteresis, micro- or surface roughness generated hysteresis, and cohesion (friction contribution from rubber wear) [1,2]. In presence of lubricant, the viscous component of friction also appears and can be interpreted as energy loss due to the viscous nature of lubricant. Contribution of different components to sliding friction depends on the macro geometry, detailed surface micro-topography, relative tangential velocity, cleanliness of surfaces, temperature, material and surface properties of rubbing bodies, applied normal load, filler material and content, lubricant and its additives, and surface treatment/coating of the harder counterpart or the rubber surface. Interaction of friction mechanisms and complexity of physical processes involved in rubber friction, however, make the friction prediction very challenging.

From engineering point of view reciprocating rubber seals are of primary importance because they are frequently used machine elements. During operation most of them slide on (apparently) smooth hard (compared to rubber) countersurface in presence of lubricant. Seals have smooth surface but the surface of harder counterpart is usually even smoother (see [3]) in order to reduce friction, rubber wear and wear induced leakage. It is well known that reciprocating rubber seals operate frequently in boundary and mixed lubrication regime. However different explanations exist in the literature for the friction contribution arisen in the boundary lubrication regime. On the one hand [4] states that the friction is determined predominantly by interaction between the solids and between the solids and the liquid. Bulk flow properties of the liquid play little or no part in friction. In other words, the friction contribution arisen in the boundary lubrication regime is considered to be due to the shearing of a thin boundary lubricant layer separating contacting surfaces or shearing of the interface between the boundary layer and the solid surfaces. Shear strength of the boundary lubricant layer is influenced by both properties of the contacting surfaces and those of the lubricant. Its magnitude can only be determined by experiments conducted at sufficiently low sliding velocity where the hydrodynamic effect is negligible. In [5], it was also pointed out that the applied normal pressure and the adhesion may induce solid/solid contact between the adhered boundary lubricant islands (discontinuous boundary lubricant layer) causing relatively high coefficient of friction. In the boundary lubrication regime, applied normal load is carried by asperity contacts and closed lubricant pools formed in the roughness valleys of harder surface. On the other hand, in [6,7], the importance of micro-hysteretic friction component is emphasized in case of boundary lubrication. The authors hypothesized that the friction contribution arisen in boundary lubrication regime is mainly due to the surface roughness generated hysteresis (micro-hysteresis). The reason why this was hypothesized is that the very thin boundary layer formed typically from few layers of lubricant molecules makes solid type asperity contacts possible. In contrast, Smith's theory (see [1]) states that if the adhesion propensity is very low (this is the case when adhesion eliminating boundary layer separates contacting surfaces) the micro-hysteretic friction

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will disappear. Consequently Smith's theory is based on "adhesion-related surface deformation hysteresis" where the decreasing adhesion propensity results in decreasing micro-hysteretic friction. Additionally Smith assumes that the micro-hysteretic friction contribution is practically independent of the nominal contact pressure.

Main objective of the current study is to investigate the contribution of micro-hysteresis to rubber friction in case of apparently smooth surfaces. In order to attain this objective it is needed to reanalyze measurement results of [6], and compare them additional test results. Like in [6], friction test results reported for nitrile butadiene rubber (NBR) are in the focus of this work because, contrary to its great practical importance, surprisingly little attention is paid in the literature to oil lubricated sliding friction of NBR squeezing against (apparently) smooth steel surface.

2. Micro-hysteresis

Nowadays considerable effort is made in the literature to study the role of micro-hysteretic component of rubber friction both theoretically and experimentally. Accurate prediction of micro-hysteretic friction contributes to the differentiation and quantification of friction mechanisms (contribution to rubber friction from macro-hysteresis, adhesion, rubber wear, etc.). Furthermore, the knowledge gained from theoretical and/or experimental works enables engineers to design rubber components or rubber friction related tribological systems with improved tribological behavior. Several studies and results prove that the micro-hysteretic friction may be dominant when rubber slides on rough (silicon carbide paper) or very rough surface (asphalt road surface). At the same time, combined experimental (see Fig. 1) and theoretical study of Mofidi et al. [6] on surface roughness generated friction showed that the micro-hysteresis may give the dominant contribution to rubber friction even in case of lubricated, apparently smooth surfaces.

[7] emphasizes also the importance of micro-hysteresis for the case when the rubber slides on apparently smooth steel surface. Mixed friction of reciprocating O-rings was analyzed numerically as well as experimentally and it was concluded that, in the boundary lubrication regime, the friction force can be explained by Persson's micro-hysteretic friction theory [8].

Conclusion of [6] is very interesting especially in the light of the fact that the friction of NBR specimens studied was complicated by very unfavorable lubrication condition, frictional heating and wear. In [6], the viscoelastic (hysteresis) friction contribution was calculated by using Persson's friction theory (see [8]) which is based on spectral description of the surface roughness. However, in [9], it was pointed out that the calculated viscoelastic contribution is very sensitive to the geometrical details of rigid asperities and hence the spectral description of surface roughness does not allow us to predict micro-hysteretic contribution accurately. At the same time, in a very recent paper, Fina and his co-authors [10] found that, in case of rough surfaces, Persson's model predicts correctly the peak value of hysteretic coefficient of friction and the sliding velocity at which it appears but results in poor correlation for the shape of the hysteretic friction master curve. The latter implies that the calculated coefficients of friction, excepting the peak value and the ones in its small vicinity, differ considerably from the measured values. However it must be mentioned that [10] did not consider friction test results for smooth surfaces. Persson's theory may also be criticized for the small strain linear viscoelastic description of rubber behavior incorporated in it because does not allow researchers to take into consideration neither the effect of large strains nor the strain amplitude dependence of storage modulus and loss factor of the rubber. The influencing effect of strain on rubber viscoelastic properties was studied, among others, in [11]. Contrary to its great importance the effect of strain on rubber viscoelastic properties is usually neglected in hysteretic friction predictions, because there is no consensus in the literature in respect of strain at which DM(T)A (dynamic mechanical (thermal) analysis) tests should be performed. Arbitrary choosing of strain value, however, may cause serious uncertainty in hysteretic friction predictions. In [12], friction tests were performed at T=27 °C to study the friction process between dry rubber disks (carbon black- and silica-reinforced BR and S-SBR elastomers) and smooth (made with polishing, $R_a = 0.52\ \mu\text{m}$) or rough ($R_a = 2.28\ \mu\text{m}$) granite balls with diameter of 30 mm. The sliding velocity and the nominal contact pressure was 5 mm/s and 0.4 MPa, respectively. In dry case, the smooth surface produced higher friction force than the rough one. In order to estimate the contribution of micro-hysteretic component to rubber friction the tests were repeated in presence of lubricating oil having dynamic viscosity of 78 m Pa s at 20 °C. In case of smooth ball, it was found that a thin boundary lubricant layer decreases the coefficient of friction drastically (from 1.55 to 0.05 for 85 phr silica-filled rubber). This experimental finding and additional calculations proved that the hysteretic component of friction can be neglected when a smooth surface is in contact with rubber. It was also concluded that the real area of contact is 3–5 times greater when the smooth ball is in contact with the rubber. Additionally, it was pointed out that wear debris attached to the granite surface decreases the surface roughness (smoothing effect of the wear debris) and increases the real area of contact.

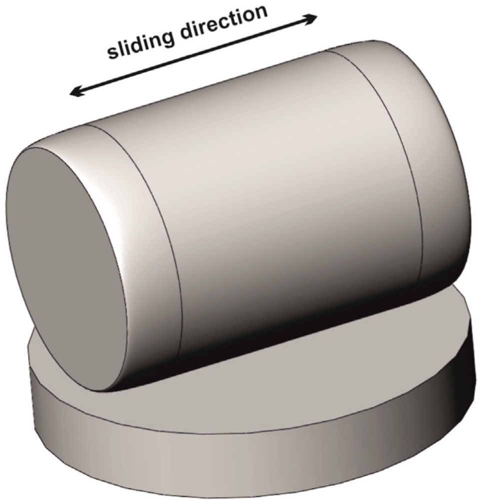

Fig. 1. Test configuration used in [6].

3. Unlubricated frictional behavior

Firstly, the most important conclusions of friction tests conducted on rubber sliding on dry, apparently smooth harder surfaces are reviewed. According to the aim of this study, most of them refer to nitrile rubber.

From the friction test results analyzed in [1] it can be concluded that when the rubber block slides on dry and smooth glass surface with a velocity lower than 1 mm/s (negligible frictional heat generation) the kinetic friction coefficient is dominated by adhesion and usually load dependent i.e. decreases with increasing applied normal pressure (nominal contact pressure). At the same time, rubber frictional resistance to sliding on dry, smooth track can be reduced by using rougher rubber specimens (smaller real