ON THE MICRO-TRIBOLOGY OF ELASTOMERIC CONTACTS

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SUMMARY
An overview of micro-tribological events, including micro-adhesion, micro-hysteresis and micro-lubrication is presented in this paper. The link between micro-lubrication and elastohydrodynamics is inseparable, but it appears that elastomer properties have diminishing importance as the scale of texture reduces. In the limit, micro-hysteresis effects give way to micro-adhesion, the latter depending critically on the harshness of micro-texture. Lubricant entrainment over asperity peaks is a function primarily of macro-texture, in particular the slope of such asperities and the void volume created by the macro-texture. This void volume acts as minute lubricant reservoirs which supply the entrainment mechanism and ultimately oppose the adhesion-generating harshness effect. There has been a limited investigation as reported in the literature of the macro-tribology of elastomeric contacts, but very little in the case of micro-events. This is surprising in view of the crucial relevance of such phenomena to an understanding of sliding seals, rubber mounts and tyre friction.

Keywords: micro-adhesion; micro-hysteresis; micro-lubrication; elastohydrodynamics, stiffening

1 INTRODUCTION
This paper describes and investigates some observable and inherently fundamental phenomena, which uniquely characterize the micro-tribology of flexible materials such as elastomers and rubbers.

Both micro-friction and micro-lubrication are considered in detail when an elastomer slides or squirms on a rigid and textured substrate. The latter if nominally smooth exhibits a micro-roughness, which may be measurable in sub-micron or even nanometre dimensions. If nominally rough, the rigid substrate also exhibits a distinctive macro-texture, which physically supports the micro-texture, and is measurable in micron or even millimetre dimensions depending on the application.

2 VISCOELASTIC PHENOMENA
When elastomer deformation takes place in a finite time interval, usually because of sliding speed, elastic properties must be replaced by their viscoelastic equivalent. The two distinctive viscoelastic phenomena, which are then observed, may be described as:

(1) Contact asymmetry, and
(2) Stiffening and softening effects.

Both of these phenomena are due to the physical interaction of the elastomer with the macro-texture of the underlying substrate in a sliding situation, and are critically speed-dependent. The first effect which occurs as speed is increased from low values is contact asymmetry, as depicted in Figure 1 below, the result of which is the well-known hysteresis component of friction [1, 2, 3].

This gives rise on its own to the classical resonance-type peak characteristic which is the main feature when the viscoelastic Young's modulus $E'$ is plotted as a function of either frequency or speed [1]. Whereas this curve has implicitly assumed constant temperature $T$, the reality is that temperature increase necessarily accompanies a rise in speed as a result of increasing frictional energy dissipation at the sliding interface. This important effect can be modelled by the following technique:

(a) Sketching a series of peak viscoelastic characteristics, each at a different temperature $T_i$ which is incrementally greater than the previous curve in accordance with the relationship:

$$ T_i = T + i\Delta T $$

where $\Delta$ is a preset increment, and $i$ has the values 1, 2, 3, etc. Note that increasing temperature moves the constant temperature curves positively along the speed axis, as shown in Figure 2.
Figure 2: Modelling the Temperature Effect in Hysteresis Friction

(b) Drawing an envelope to the separate constant temperature curves, again as shown in Figure 2, this representing the reality of combined temperature and speed increase. We observe that the envelope curve also exhibits the well-known viscoelastic peak but is considerably flattened in the process.

Both the stiffening and softening effects due to speed and temperature respectively have been implicitly included in formulating the resultant characteristic evident in Figure 2 above. On a physical basis, stiffening is an apparent increase in the Young’s modulus due to the frequency of indentation of the elastomer surface by the macro-texture of the substrate - whereas softening represents its actual decrease due to temperature rise from increasing energy dissipation. Further details of these mechanisms may be found elsewhere [3].

3 EQUIVALENT ENERGY DISSIPATION

The dynamic draping pattern of a sliding elastomer about the macro-texture of the substrate combined with a superimposed stiffening-softening effect as frequency or speed is increased is considerably complex, and the detailed deformation is still unknown. This makes the calculation of consequential energy dissipation virtually impossible. However, an equivalent energy dissipation technique has been developed [4] which enables us to proceed without details of contact asymmetry, etc. This is based upon a parallel or similarity between the change from sinusoidal to random deformation energy input in vibration theory on the one hand, and the change from symmetrical to asymmetrical dynamic draping in the case of a sliding elastomer on the other. Using this technique, we then identify an equivalent damping parameter, c, such that the same energy dissipation per cycle $E_d$ is obtained. It has been shown [1, 2, 3] that for contact symmetry about sinusoidal asperities:

$$E_d = \pi \omega \delta_0^2$$  (2)

where $\omega = V / \lambda$ is the dynamic frequency input to the sliding elastomer from the macro-texture, $\lambda$ is the mean wavelength of same, $V$ the speed of sliding, and $\delta_0$ the amplitude of deformation.

Equation (2) can also be expressed in terms of the tangent modulus $\tan \delta$ of the elastomeric material, thus putting $\tan \delta = c \omega / E' L$:

Putting the hysteresis friction force $F_{hyst} = E_d / \lambda$, and $f_h = F_{hyst} / W$, where the normal load $W$ is given by $W = E' L \delta_0$, the coefficient of hysteresis friction finally becomes:

$$f_h = \pi \delta_0 \tan \delta$$  (3)

The viscoelastic nature of $f_h$ is at once apparent from the tangent modulus parameter in Equation (3).

4 MICRO-HYSTERESIS

Consider now the effects of reducing the scale of texture from macro- to micro-dimensions, bearing in mind the consequent cyclic energy dissipation given by Equation (2) or Equation (2A). Assume that both sliding speed $V$ and temperature $T$ are held constant as the value of $\lambda$ diminishes. The frequency of indentation $\omega$ is seen to increase, but the square of the amplitude of deformation $\delta_0$ reduces at a faster rate. Thus, the overall value of $E_d$ diminishes, even without considering $\tan \delta$ which has also diminished [3]. It is evident that the contribution of micro-hysteresis to overall friction has ultimately reduced to virtually zero value.

On a physical level, the dynamic draping suggested in Figure 1(b) gradually reduces to low and ultimately zero value according as the scale of events reduces from macro- to micro-dimensions. This is due to the increasing value of $E'$ from frequency stiffening. The overall effect is that the sliding elastomeric material, while continuing to drape dynamically about the macro-texture of the substrate, only touches the peaks of the micro-texture. We can then say that the role of micro-hysteresis becomes ultimately indistinguishable in the limit from that of micro-adhesion, as dealt with in the next section.

5 MICRO-ADHESION

The classic definition of adhesion is a thermally-activated molecular-kinetic stick-slip action occurring within a very thin surface layer of the sliding elastomer. This mechanism is due to the sequential making, stretching and breaking of molecular bonds at the elastomer surface. It has been estimated that bond formation takes place across the sliding interface to a total depth of at least 100 Å. Thus, maximum adhesion
would occur between nominally flat smooth surfaces provided the latter are sufficiently clean. In practice, all “smooth” substrata exhibit surface contamination which may be sufficient to negate the bond formation mechanism. The presence of a micro-roughness on the apparently smooth substrate fulfills the following roles simultaneously:

1. It ensures intimate contact with the sliding elastomer at asperity peaks by breaking through adhesion-inhibiting surface films.
2. At the same time, the total area of intimate contact becomes only a small fraction of the nominal or smooth area, thus reducing the adhesional friction force accordingly.

Micro-adhesion is therefore still due to the well-documented thermally-activated molecular-kinetic stick-slip action now occurring at the tips of surface micro-roughness.

6 MICRO-LUBRICATION

The presence of even the smallest amount of lubricant on a surface creates what might be described either as macro- or micro-lubrication depending upon the scale of events. Consider in detail the effects when a thin adherent film of liquid exists on the macro-texture of the rigid substrate in the presence of a loaded sliding elastomer. For a substrate with distinctive macro-texture but no micro-texture whatever, hydrodynamic entrainment of the film over asperity peaks even at very low sliding speeds creates a macro-entrainment of lubricant over individual asperities of the macro-texture.

\[
\varepsilon_{mr} \geq h^* \tag{4}
\]

where \( \varepsilon_{mr} \) denotes the micro-roughness amplitude, and \( h^* \) the entrained film thickness which would otherwise exist at macro-asperity tips in the absence of micro-roughness. We observe that whereas \( \varepsilon_{mr} \) is fixed in a given application, the magnitude of \( h^* \) is speed-dependent. At lower sliding speeds, the inequality in Equation (4) is preserved, and adhesion prevails. On the other hand, raising the sliding speed \( V \) will restore the film-thickness to a value exceeding the macro-roughness amplitude, thereby eliminating localized adhesion. A convenient way to visualize the interplay of these two effects is to imagine that both interacting surfaces---the underlying macro-texture and the draping elastomer---are initially at rest. As sliding speed is introduced, the draped pattern of the elastomer shown in Figure 3 is raised infinitesimally without altering its shape due to hydrodynamic pressure-wedge formation along its leading flank. Eventually, by increasing sliding speed, the magnitude of this infinitesimal hydrodynamic uplift is such that \( h^* \) exceeds \( \varepsilon_{mr} \) and the macro-elastohydrodynamic fluid entrainment mechanism is fully restored at asperity peaks.

It might be surmised that during the period when Equation (4) applies, there would be an attempt by the elastomer to drape dynamically about the individual elements of the micro-texture. In fact, this is entirely precluded by the elastomer stiffening phenomenon described earlier in this paper. For a given sliding speed \( V \), the frequency of indentation \( \omega \) according to the relationship \( V = \alpha \lambda \) increases dramatically according as \( \lambda \) reduces from macro- to micro-dimensions. The consequent local stiffening phenomenon means effectively that hydrodynamic entrainment action forces the elastomer upward at asperity peaks as though it were a rigid body. This is the essence of micro-lubrication theory in the presence of a micro-roughness.

7 APPLICATIONS

The slipping and skidding behaviour of a pneumatic tyre on a wet pavement surface remains one of the key applications of micro-tribological events. This is especially true for thin-film situations which occur after a light shower of rain or even a heavy night dew. The local squirming and slipping of tyre tread elements during rolling and cornering behaviour may induce
tread/surface separation with consequent serious safety implications. Significantly, the nature of tyre element slippage in rolling for a given nominal speed of forward travel is such that velocity of slippage increases non-linearly towards the rear of contact. This means that viscoelasto-hydrodynamic effects start from the rearmost point of "contact", and produce the phenomenon of rearward contact erosion, being entirely a thin-film characteristic. At the same time, thick-film lubrication may induce front erosion from dynamic hydroplaning.

Other applications of macro- and micro-tribological events are the sealing performance of an elastomeric seal on a rapidly-rotating lubricated shaft, the sliding action of a hypodermic syringe stopper, and the cleaning action of windscreen wipers. In all of these cases, a flexible member is loaded against a lubricated, moving and textured substrate, and these and other examples have been dealt with at length elsewhere [3].

The key factor is that whereas macro-events lead to significant elasto-hydrodynamic interactions, micro-events appear to cause the elastomer to behave as a rigid body. This is because the stiffening effect appears to dominate, leading to the general conclusion that micro-elastohydrodynamics becomes non-existent. This also means that micro-hysteresis effects on the finer micro-texture also disappear, leaving only micro-adhesion. The key characteristic of effective micro-texture in promoting micro-adhesion is its sharpness or harshness, which is most effective in counteracting and penetrating entrained lubricant.

8 CONCLUSION

An overview of micro-tribological events has been presented in this paper, including micro-adhesion, micro-hysteresis and micro-lubrication. The link between micro-lubrication and elastohydrodynamics is inseparable, but it appears that elastomer properties have diminishing importance as the scale of texture reduces. In the limit, micro-hysteresis effects give way to micro-adhesion, the latter depending critically on the harshness of micro-texture. Lubricant entrainment over asperity peaks is a function primarily of macro-texture, in particular the slope of such asperities and the void volume created by the macro-texture. This void volume acts as minute lubricant reservoirs which supply the entrainment mechanism and ultimately oppose the adhesion-generating harshness effect.

9 REFERENCES