

## Rubber friction

First principle calculations of frictional forces for realistic systems are generally impossible, since friction is an interfacial property, often determined by the last few uncontrolled monolayers of atoms or molecules at the interface. In diamond, a huge friction results between two clean surfaces in ultra high vacuum, because of the strong interaction between the surface dangling bonds. However, saturation of these bonds by a hydrogen monolayer (as they generally are in reality) leads to extremely low friction. Since most surfaces of practical use are covered by several monolayers of contaminant molecules of unknown composition, a quantitative prediction of sliding friction coefficients is not possible. An exception to this may be rubber friction on rough surfaces.

Rubber friction is of great practical importance, e.g., in the context of tires, wiper blades, conveyor belts and rubber seals. Rubber friction on smooth substrates, e.g., on smooth glass surfaces, has two contributions, adhesive (surface) and hysteretic (bulk). The former results from the attractive forces between the rubber surface and the substrate. Surface forces are often dominated by weak attractive van der Waals interactions. For very smooth substrates, because of the low elastic moduli of rubber-like materials, this weak attraction may result in a nearly complete contact at the interface, even when the applied squeezing force is very small. The result is the large sliding friction force usually observed. For rough surfaces, however, the adhesive contribution will be much smaller because of the small contact area. The actual contact area between a tire and a road surface, for example, is typically around 1% of the nominal footprint contact area, i.e., of order of  $1 \text{ cm}^2$  for the tire of a family car. Under these conditions, bulk (hysteretic) friction should prevail. For example, the extreme temperature-dependence of tire-road friction reflects the strong temperature dependence of the viscoelastic bulk properties of rubber.

The main contribution to rubber friction when a rubber block slides on a rough substrate, i.e., a tire on a road surface, is the viscoelastic energy dissipation in the surface region of the rubber. These result from the pulsating forces acting on the rubber surface from the substrate asperities (see Figure 1). Recently we developed a theory that describes this dissipation process accurately, and also predicts the velocity dependence (and the time-history dependence) of the rubber friction coefficient. The results depend only on the (complex) viscoelastic modulus  $E(\omega)$  of the rubber and the substrate surface roughness power spectra  $C(q)$ , and agrees well with experiment.

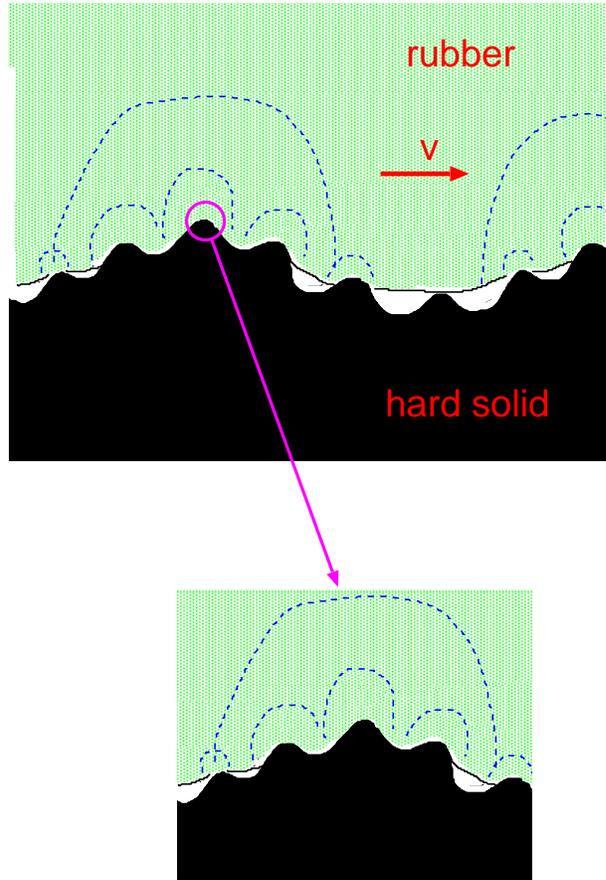


Figure 1: The road asperities exert pulsating forces on the sliding rubber block, leading to energy dissipation in the rubber via its internal friction. Most of the energy dissipation occurs in the volume elements bounded by the dashed lines. The rubber viscoelastic deformations in the large volume elements are induced by the large road asperities, while the smaller dissipative regions result from the smaller asperities distributed above the large asperities. Calculations of rubber friction must include the viscoelastic energy dissipation induced by all asperity sizes. The local temperature increase (flash temperature) in the rubber resulting from the energy dissipation must also be considered analysis.