Present research activity

My main research activity at present is contact mechanics, adhesion, rubber friction and crack propagation in rubber.

Contact Mechanics

A central problem in tribology has been to relate the real contact area between surfaces to the force acting on them. I have developed a new approach to this problem which forms the basis for my theories of rubber friction and adhesion. The basic idea behind the contact theory is that it is very important not to *a priori* exclude any roughness length scale from the analysis. The theory shows how the (apparent) contact area between two solids changes as the system is studied at different magnification. The true atomic contact area is obtained by increasing the resolution to atomic length scale. The theory can be applied to viscoelastic solids both stationary and in sliding contact. For small applied load the theory predicts that the contact area is proportional to the load (as also found experimentally), where the coefficient of proportionality is determined by the surface roughness power spectra and by the elastic (or viscoelastic) modulus of the solids.

Adhesion

The contact mechanics theory can also be applied to study adhesion between elastic solids. I have considered in detail the case when the surface roughness can be described as a self affine fractal, and shown that when the fractal dimension $D_{\rm f} > 2.5$, the adhesion force may vanish, or be at least strongly reduced. An important result is that even when the surface roughness is so high that no adhesion can be detected in a pull-off experiment, the area of real contact (when adhesion is included) may still be several times larger than when the adhesion is neglected. Since it is the area of real contact which determines the sliding friction force, the adhesion interaction may strongly affect the friction force even when no adhesion can be detected in a pull-off experiment. The theory is in good agreement with experimental data.

Adhesion in Biological Systems

How can a fly or a cricket walk on a glass window, or a lizard move on a stone or concrete wall? The adhesive microstructures of insects and lizards are the result of millions of years of development driven by the principle of natural selection. One may expect the adhesive structures to be highly optimized, and it is clear that a good understanding of the construction and function of the adhesive structures may lead to new improved man-made adhesives. I have studied adhesion relevant to biological systems, e.g., flies or lizards, where the adhesive microstructures consist of hierarchical arrays of thin fibers and plates. I have shown that the hierarchical structure results in an adhesive system that is soft on all length scales from nanometer to millimeter, which is of fundamental importance for adhesion to natural surfaces, which have roughness on all length scales. I have also shown that if the fibers are too thin or too long the fiber array is unstable, and fiber bundling results in a strong degradation of the adhesive system, as indeed observed in the first man-made fiber adhesive.

Rubber Friction

Another important application of the contact mechanics theory is to rubber friction. When rubber slides on a hard, rough substrate, the surface asperities of the substrate exert oscillating forces on the rubber surface leading to energy “dissipation” via the internal friction of the rubber. I have developed a theory which shows how the resulting friction force depends on the nature of the substrate surface roughness and on the sliding velocity. In particular, I have studied the case when the substrate surface has a self affine fractal structure. The temperature increase (flash temperature) which occurs in the rubber-substrate asperity contact regions is taken into account in the analysis and turns out to be of fundamental importance in friction dynamics, e.g., it gives rise to memory effects where the friction at time t depends on the sliding motion for all earlier times $t' < t$. The flash temperature is also the reason why the rubber friction force usually decreases with increasing sliding velocities for v larger than $\sim$ 1 cm/s, and also explains why wide tires usually exhibit higher friction than narrow tires. The theory forms the basis for understanding and optimizing modern ABS-breaking systems.

There is a strong drive by tire companies to design new rubber compounds with lower rolling resistance, higher sliding friction and reduced wear. Until recently, these attempts are mainly based on a few empirical rules and on very costly trial-and-error procedures. The theory I have developed is already used in the design of new rubber compounds for tires.

Crack Propagation in Rubber

Crack propagation in rubber-like materials has been studied for many years because of its importance for rubber wear and other rubber applications. The standard approach is based on the Barenblatt model for the crack tip process zone. However, this approach is very complicated and cannot easily be generalized to include other important effects such as the non-uniform temperature distribution at the crack tip. I have developed a much more simple theory of crack propagation in viscoelastic solids. The theory results in a relatively simple expression for the energy per unit area, $G(v)$, to propagate a crack, as a function of the crack-tip velocity v. The theory includes the non-uniform temperature distribution (flash temperature) in the vicinity of the crack tip, which has a profound influence on $G(v)$. At very low crack-tip velocities, the heat produced at the crack tip can diffuse away, resulting in very small temperature increase: in this *low-speed* regime the flash temperature effect is unimportant. However, because of the low heat conductivity of rubber-like materials, a very large temperature increase (of order $\sim 700\ ^\circ$C) may occur close to the crack tip already at moderate crack tip velocities. I have shown that this will drastically affect the viscoelastic energy dissipation close to the crack tip, resulting in a *hot-crack* propagation regime. The transition between the low-speed regime and the hot-crack regime is very abrupt, which may result in unstable crack motion, e.g. stick-slip motion or catastrophic failure, as observed in some experiments.

Crack propagation in rubber, and rubber friction on rough substrates, have great similarities and both are fundamentally affected by the flash temperature. In fact, in my treatment of the rubber crack propagation problem I greatly benefited from my earlier studies of rubber friction.