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Adhesion and friction

Lecture 33

Wetting

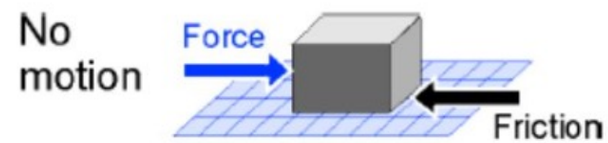


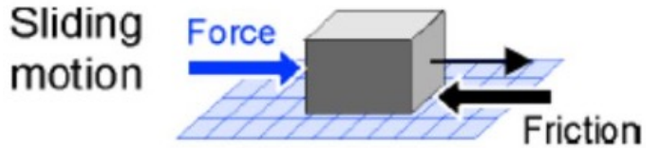
Lecture 35

Adsorption

Friction

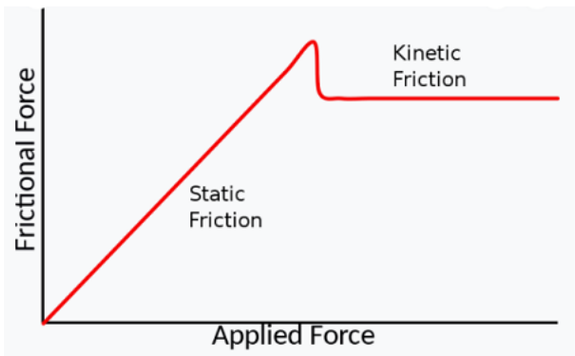
When two solid objects are in contact under a normal load (such as gravity), a certain amount of force is needed to initiate and maintain tangential movement with respect to one another.





Two types of frictional force are involved in such a process:

- the force necessary to <u>initiate</u> movement, i.e. to overcome <u>static</u> friction,
- the force necessary to <u>maintain</u> movement, i.e. to overcome <u>kinetic</u> friction.



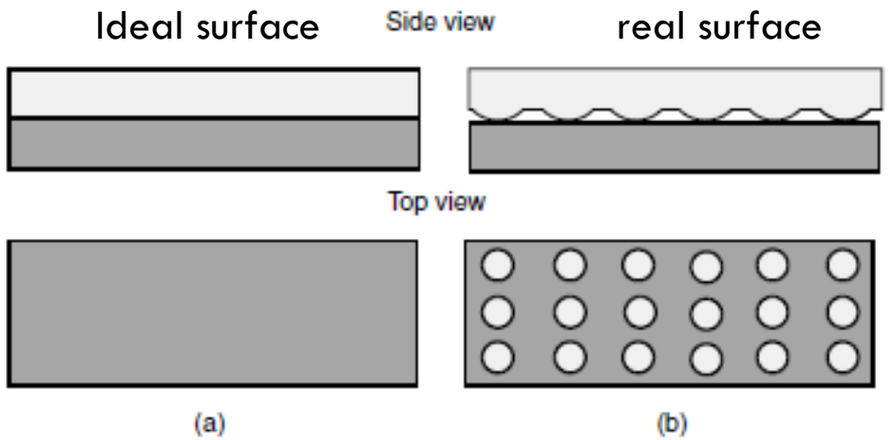
The three laws of friction can be stated as follows:

1) The frictional force is proportional to the applied load.
2) The force is independent of the apparent area of contact between the two objects.
3) The kinetic frictional force is independent of the sliding velocity.

Sources of friction - 1

Q1

- **Adhesion between points of actual contact between the surfaces.**
- Even a super-smooth surface usually has corrugations of 5 - 10 nm so that the "true" area of contact between two such surfaces is less that the apparent area.
- At the areas of contact, the two surfaces are bound by adhesion forces (intermolecular plus in some cases physical interactions, interpenetration).



For the two surfaces to move tangentially, the adhesion must be sheared or broken.

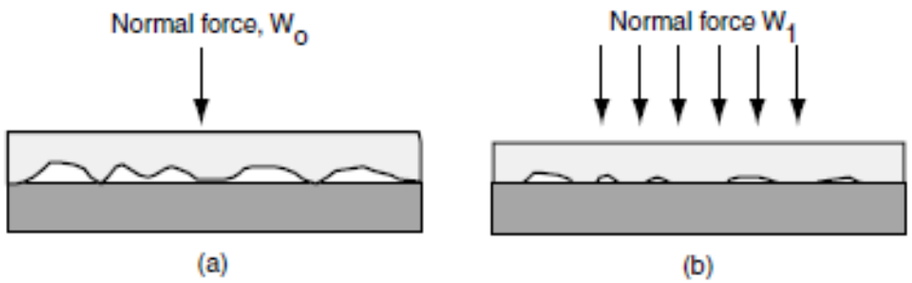
If A = actual area of contact and s = adhesive shear strength, the frictional force due to adhesion is

$$F_{ad} = A\,s$$

Adhesional friction is a surface phenomenon.

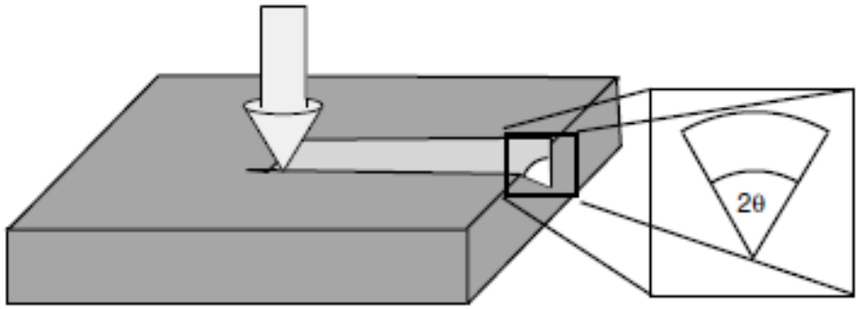
Sources of friction - 2

- **Deformation** – this is a bulk physical contribution. It arises as a result of deformation, cracking, or plowing caused by penetration of the corrugations of one surface into those of the other.
- The important unknowns include the real area of contact between surfaces, *A*, the shear strength of the points of contact, *s*, and the deformation component.
- If a normal force *W* is applied to the system, we expect that the added pressure on the corrugations will cause deformation which increase in the real area of contact, as illustrated.



- If the materials respond to the added pressure by plastic deformation (i.e., a permanent change in the shape of the corrugations), the real area of contact can be written as: $A = W/\tau_o$
- Where τ_o is the yield strength of the interface.

Material response



- A material can respond to the applied load with an elastic (i.e. reversible) deformation, or a viscoelastic (i.e. reversible but time-dependent) deformation.
- If the two surfaces are of different materials, with different hardness, asperities (i.e. corrugations) on the hard surface will tend to plow into the soft surface, forming grooves.
- The force required for such a process will depend on the cross section of the groove as well as the yield strength of the soft material.
- The cross-section will depend on the geometry of the asperity and the depth it penetrates into the soft surface.
- So friction is a combination of adhesional and plowing contributions. It is usually difficult to separate the relative roles of each; that is, the two are not necessarily directly additive in their contribution.
- If the asperities on a surface are known to be relatively blunt, it can usually be assumed that they will not make a significant contribution in terms of the plowing mechanism.

Four types of surfaces

Q2

Friction depends on the hardness and strength of each material.

We will consider four categories of materials:

1. Metals and their oxides;
2. Relatively isotropic crystalline materials;
3. Layered crystals;
4. Polymeric (e.g., amorphous) materials.

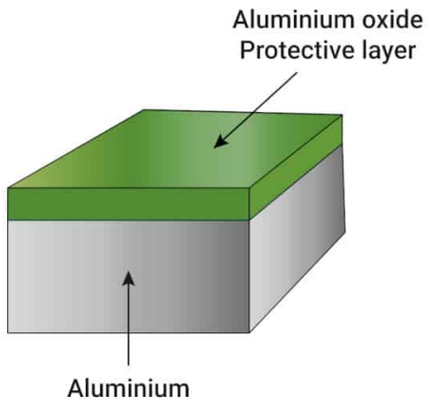
Each type of surface may have its own unique frictional characteristics related to the chemical and physical nature of the relevant interactions.

The unit-less **friction coefficient** μ helps us categorise friction:

$\mu = F/W$ F = friction force W = applied load

1. Metal/metal oxide surfaces

- Most metals are covered with at least a monolayer of oxide. In practice, the friction between metal surfaces should be considered that between oxide layer or composite surfaces in which there are oxide–oxide, oxide–metal, and metal–metal components.
- Several patterns of behaviour may be observed, depending primarily on the strength of the oxide and its bonding to the bulk metal surface.
- In aluminium, for example, the oxide layer is much harder than the metal. The frictional interaction therefore easily deforms (plastic deformation) the metal supporting the oxide, and then the oxide layer, a thin film with little inherent strength, then breaks under even small loads. Friction, then, is relatively independent of load.
- Copper, on the other hand, generally shows a dependence of friction on load, indicating that the oxide layer is relatively strong and better matched to the characteristics of the underlying metal.
- Clean copper has a much higher friction coefficient (μ=6.8) than copper oxide (μ~0.8).

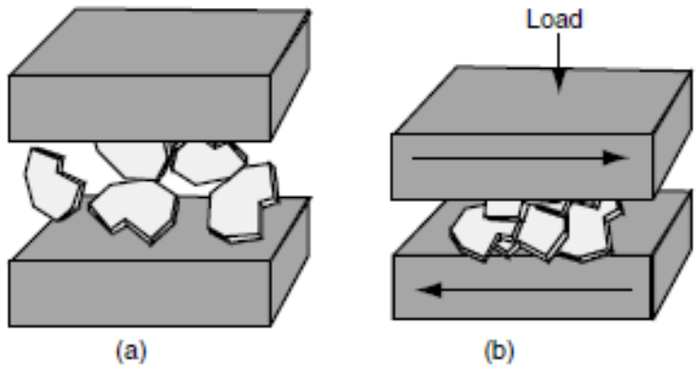


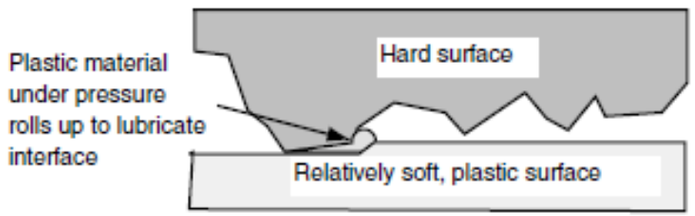
2. Relatively isotropic crystalline materials

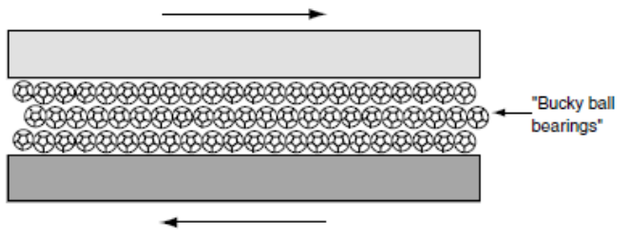
- NaCl, diamond, sapphire and other similar minerals, and solid non-metallic elements such as krypton.
- The softer members of the have frictional coefficients 0.5–1.0.
- The harder, more brittle substances such as NaCl tend to suffer extensive surface damage due to cracking.
- Diamond and sapphire have low μ values (0.1), but its value depends on the load, with these materials deforming elastically rather than plastically.
- Under very clean conditions, μ for diamond has been found to rise to 0.6, suggesting that some adsorption of a monomolecular water layer or slight surface oxide formation may act to lubricate the diamond surface naturally.

3. Layered Crystalline Materials

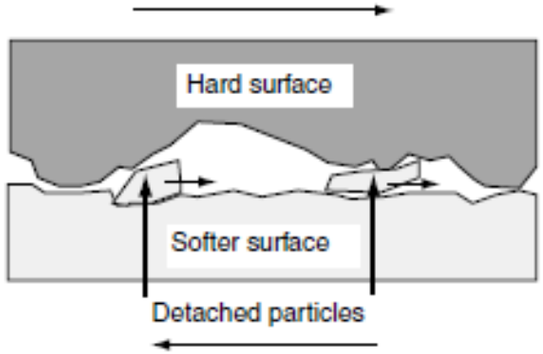
- Graphite, MoS_2, and talc, known as good lubricants.
- The large faces represent surfaces of lower surface energy.
- The intermolecular forces involved in the adhesional component of friction along the large, flat surfaces are significantly less than those at the narrow edges.
- The result is a lower shear strength along those faces and a lower μ.
- For MoS_2 , the intermolecular forces in the crystal are relatively weak.
- Graphite, on the other hand, has a low coefficient of friction (0.1) in air but a higher value (0.6) in vacuum. The adsorption of gases at the interface probably weakens the adhesional forces between the parallel faces.
- Other mechanisms, yet to be fully explored, may also be involved. For example, the "rollup" of graphite layers in front of the sliding face may produce a "ballbearing effect" on the motion. Buckyballs (C_{60}) may also have this effect.







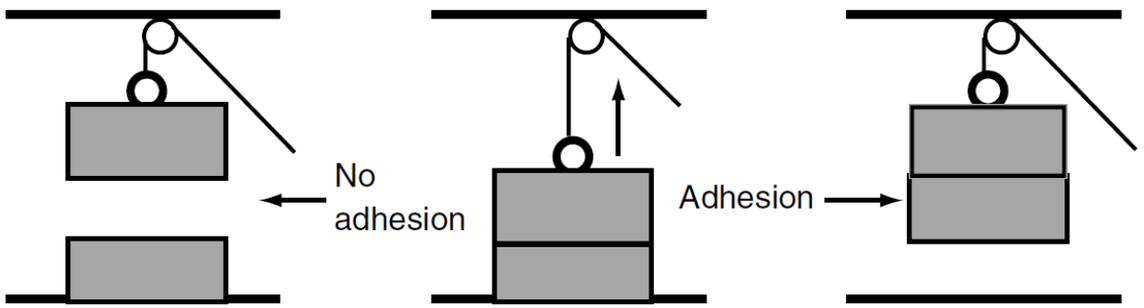
4. Polymeric materials



- The static friction is significantly greater than the kinetic component, and the value is load-dependent.
- In polymers the relative mobility of polymer units at an interface is high, and chain interpenetration between surfaces may occur, leading to a relatively strong adhesive joint, and therefore a high static friction.
- Once sliding is initiated, the relatively low shear strength of most polymers allows for the detachment of a thin layer of polymer from the sliding surface, which then acts as a boundary layer lubricating film.
- For metal–polymer interfaces the effect may be significant, since one is now going from a situation of metal–polymer sliding contact to one of polymer–polymer contact, which would be expected to have a much smaller inherent coefficient of friction.

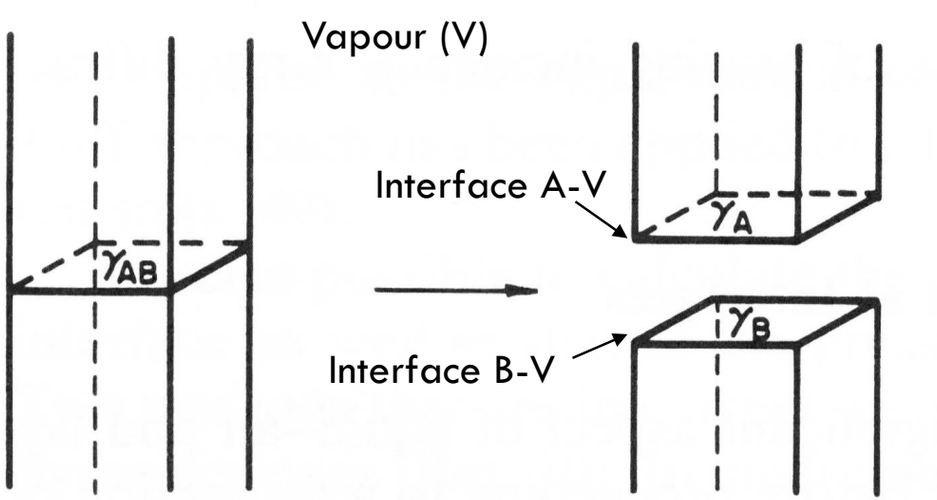
Adhesion

Adhesion can be simply defined as the phenomenon that allows a mechanical force (in excess of any frictional forces) to be applied to two contacting objects without those two objects becoming separated.



Myers, D. *Surfaces, Interfaces and Colloids - Principles and Applications. Second edn, (VCH Publishers Inc. , 1999).*

Thermodynamic Definition - Work of adhesion



If two materials A and B in contact are pulled apart inside a third phase (V, vapour), the original interface is destroyed and two new ones are created.

The work of adhesion is the work W_{AB}, per unit area, required to separate A and B beyond the range of their forces of interaction. Thus,

$$W_{AB} = \gamma_{AV} + \gamma_{BV} - \gamma_{AB}$$

The adhesive energy is a difficult property to measure, and it hard to find the actual contact area between two different materials since this is almost always much less than the geometric area.

This is why simply pressing two solids together does not produce adhesion (except for molecularly smooth crystals like mica) and a 'glue' must be used to dramatically increase the contact area.

The main function of a glue is to facilitate intimate molecular contact between two solids, so that strong short-range van der Waals forces can hold the materials together.

Thermodynamic vs practical adhesion

- In the thermodynamic model of adhesion, **reversible** work is done to separate two surfaces by overcoming intermolecular interactions between the interfaces.
- Mostly non-covalent interactions such as van der Waals forces and electrostatic interactions should be sufficient for bonding.
- This ideal model provides the upper bound for an ideal adhesion, assuming a reversible separation process. In reality, two processes are common:

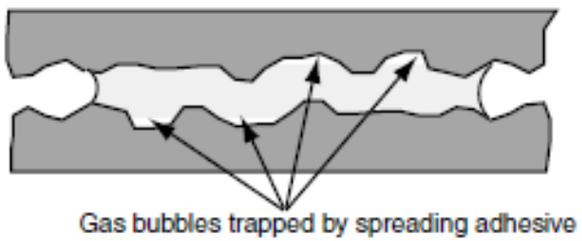
  1. Inevitable presence of flaws that are associated with the interfacial zone (next page). When stress is applied to a joint, it tends to concentrate at such flaws, so that the local stress is significantly greater than the average value. When the local stress exceeds the local strength, failure occurs.

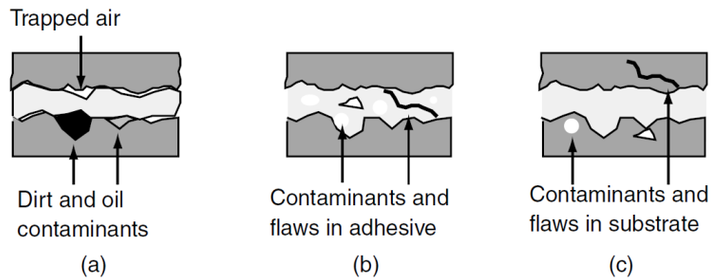
  2. Irreversible viscoelastic processes dissipate energy and reduce the adhesive forces

- Both factors reduce the strength of adhesion in real systems.

Practical adhesion

- An ideal glue needs to wets the surface well to be joined, and thermodynamically just dispersion forces should be sufficient.
- In practice even glues that wet the surface well (low contact angle) have many potential defects.





- Since all surfaces are rough, an adhesive applied to such surfaces will entrap air bubbles, water or oil droplets, dust, reducing the area of contact of adhesive with the surfaces and reducing the effectiveness of the bond.

Forces Needed for Strong Adhesion

Q3

- van der Waals forces fall off rapidly with distance (as $1/r^6$), so interacting surfaces must be as close as possible, typically 0.2–0.5 nm. Beyond that distance, such interactions will be weak.
- Intimate molecular contact between phases is a necessary, but not sufficient, condition for good adhesion.

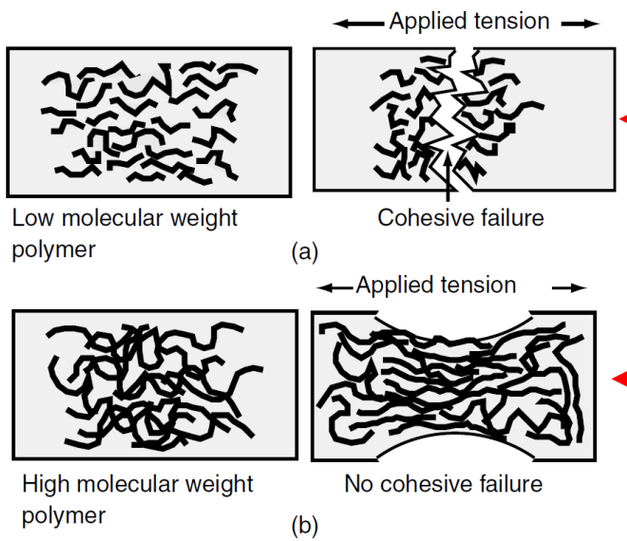
TABLE 19.2. Values of Attractive Molecular Interactions at Interfaces

Type of Interaction	Approximate Energy Range (kcal mol^{-1})
Van der Waals	
Dispersion	5
Dipole–dipole	0–10
Dipole-induced dipole	0–0.5
Hydrogen bonding	0–40
Chemical bonds	
Covalent bonds	15–170
Ionic bonds	140–250
Metallic bonds	27–83

Myers, D. Surfaces, Interfaces and Colloids - Principles and Applications. Second edn, (VCH Publishers Inc. , 1999).

Polymeric adhesives

- Most adhesives are polymers as they have high mechanical strength at high molecular weight, i.e. they transmit stress without failure
- Molecular entanglement is the reason that leads to successful bonding
- Molecular entanglement dissipates stress forces, and provides a good mechanism to back up intermolecular forces for producing good adhesion



weak interaction among adjacent chains; movement of one chain past another is easy and the tensile or shear strength is low.

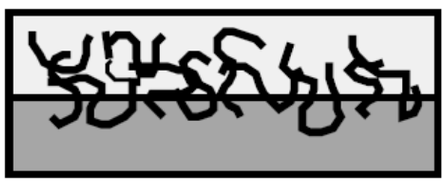
chain interactions are greatly increased, chains are entangled, and the material exhibits a much greater strength: it stretches, but resists a much greater force before failing

Four categories of adhesion

A sharp interface with weak intermolecular interactions. e.g. a nonpolar polymer (e.g., polyethylene) and a polar polymer (e.g., polyvinyl alcohol–polyvinyl acetate copolymer). Only dispersion forces, with little chain entanglement due to the inherent incompatibility of the two polymers. A joint of very poor strength.



(a)



(c)

Significant interpenetration of the adhesive into the surfaces to be bound, as they are mutually miscible. Significant entanglement leads to a strong joint, even in the absence of strong intermolecular interactions.

A sharp interface with specific chemical interactions, e.g. a polymer with groups capable of hydrogen bonding or acid–base interactions (-OH, -NH-, or -COOH) interact strongly with a metal or metal oxide surface (M_n or –M-O-M-), but no entanglement is possible. Significant mechanical strength.



(b)



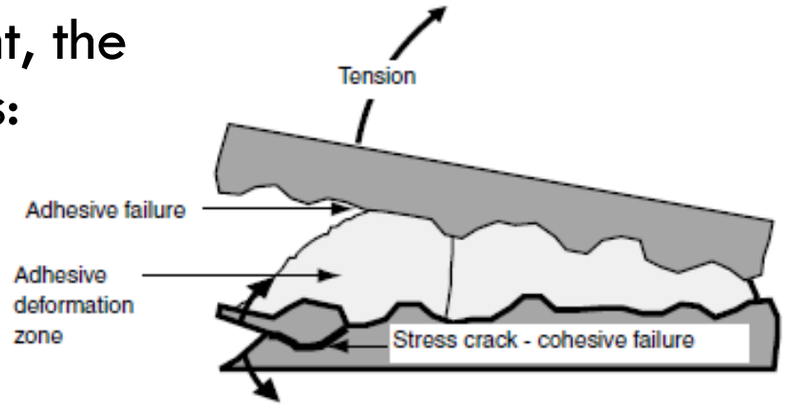
(d)

Physical or mechanical interlocking of the two surfaces, e.g. when a molten polymer or pre-polymer mixture is applied to a rough surface under condition where it can flow into the solid surface irregularities.

Adhesive failure

When a tension or shear strain is placed on a joint, the energy may be dissipated by several mechanisms:

- adhesive failure
- cohesive failure
- plastic, elastic, or viscoelastic stretching of the adhesive and/or one or both substrates.



In practice, bond failure in a "proper" adhesive joint will seldom occur at the interface. Instead, failure will occur in a weak boundary layer near the true interface, or in the weaker of the two bonded phases.

All three possibilities for failure occur.

Learning outcomes

After this lecture you should be able to

- Define friction and adhesion
- Describe how intermolecular forces affect both surface phenomena
- Apply considerations of surface energy to estimating both phenomena

Reading

Myers, D. *Surfaces, Interfaces and Colloids - Principles and Applications. Second edn, (VCH Publishers Inc. , 1999). (Electronic copy in library)*

Chapter 18 on Friction

Chapter 19 on Adhesion