FRICTION, WEAR AND LUBRICATION

MEMM 1343

THE TRIBOLOGICAL SYSTEM

A tribological system describes only a section of an entire system. Thus, for analysis, it is essential that the entire system is defined. Here, a distinction is made between open and closed tribo systems:

Closed tribo systems refers to tribological systems in which the system elements are permanent parts of the system beyond the duration of loading, and constantly participate in the tribological processes. The wear processes of all participating system elements must therefore be taken into consideration in relation to the operability. Examples of these are lifetime-lubricated bearing systems.

Open tribo systems on the other hand, are characterized by having one or more tribo elements which are moved through the system, and are not continuously in tribological contact. This is for example, the case for flowing precursor products or counter-bodies, such as a chain drive. Material processing takes place in open systems, in which new material is constantly fed in for processing. With open tribo systems, only the wear processes of the elements permanently installed in the tribo system, for example the tool for material processing or the conveyor belt of a bulk material system, are considered.

A tribological system has functional character, and performs technical tasks which are either energy-, material-, or signal-oriented, as shown in Table 1.

The tribological properties of the system depend upon the system function, the complex of loads, and the structure. The complete description of the tribological system is a basic prerequisite for the consideration, evaluation and design.

Table 1: Functional ranges of tribological systems.

Functional range	Examples of tribo systems and tribo-technical components
Guidance	Plane bearings, rolling bearings, linear guidance, running fit
Retardation of motion	Friction brakes, shock absorbers
Power/energy transmission	Gearwheels, belt drives, clutches, piston rings/cylinders, cams/tappets, turbines, articulated joints
Information transfer	Control gears, relays, read heads, printers
Sealing	Linear seals, stuffing boxes, radial shaft seals, piston ring-type sealing, piston seals, abradable coatings
Material transport	Wheel/rail, tire/road, conveyor belt, dredging shovel, chute, pipeline, pump, heart valve
Material separation	Centrifuges, cutting tools for turning, milling, drilling, grinding
Material crushing	Ball-mill, jaw crusher, shredder
Material forming	Forming tools for forging, drawing out, extruding, rolling, bending
Primary material shaping	Primary shaping tools for injection-molding, die-casting, gravity die-casting, sintering

As shown in Figure 1, this gives rise to interactions on the surface of the solid. While the base body is always a solid object, the counter-body and also the intermediate material can be either liquid or gaseous. The complex of loads and the structure determine the wear behavior of the tribo system. The analysis of a tribological system is performed in four steps, and gives indications for optimization potentials in the interest of wear. The system analysis embraces the following points:

1) Characterization of the technical functions of the tribo system.

2) Definition of the complex of loads.

3) Characterization of the structure of the tribo system by:
   (a) the elements participating in wear processes;
   (b) the relevant properties of the elements, including the contact-geometrical areas;
   (c) the interactions between the elements.

4) Definition of the frictional and wear parameters.

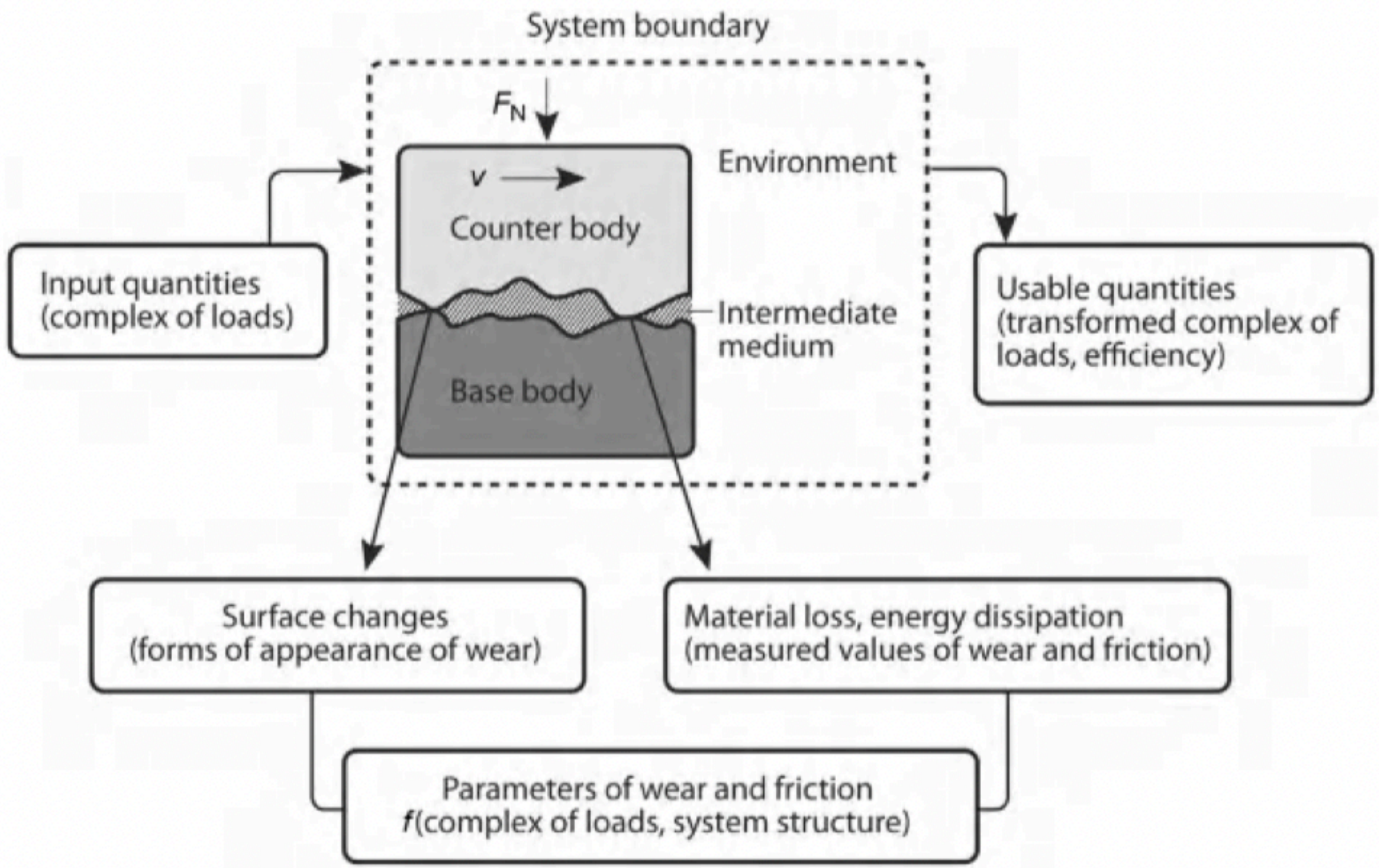


Figure 1: Schematic representation of a tribological system.

For the analysis of a tribo system, the interactions occurring between all elements must be considered. The changes to the tribo elements over a period of time in respect of their material and form properties require a time-dependent analysis. The result of this analysis is the operational parameters. The efficiency depends upon the loss parameters (frictional force, amount of wear).

Friction and wear are surface phenomena, and are dependent on the material properties of the participating elements, the tribo contact area, and the chemical and thermal loading. Under technical boundary conditions, a three-dimensional (3-D) surface region with a depth of from a few atomic layers up to several 100 mm is considered. When surface-treated tribo bodies are used, this can include the boundary surface between the base material and the coating material (interface), as shown in Figure 2. This view is useful, as most mechanical and thermal loading contributions to tribological loading are of this order of magnitude.

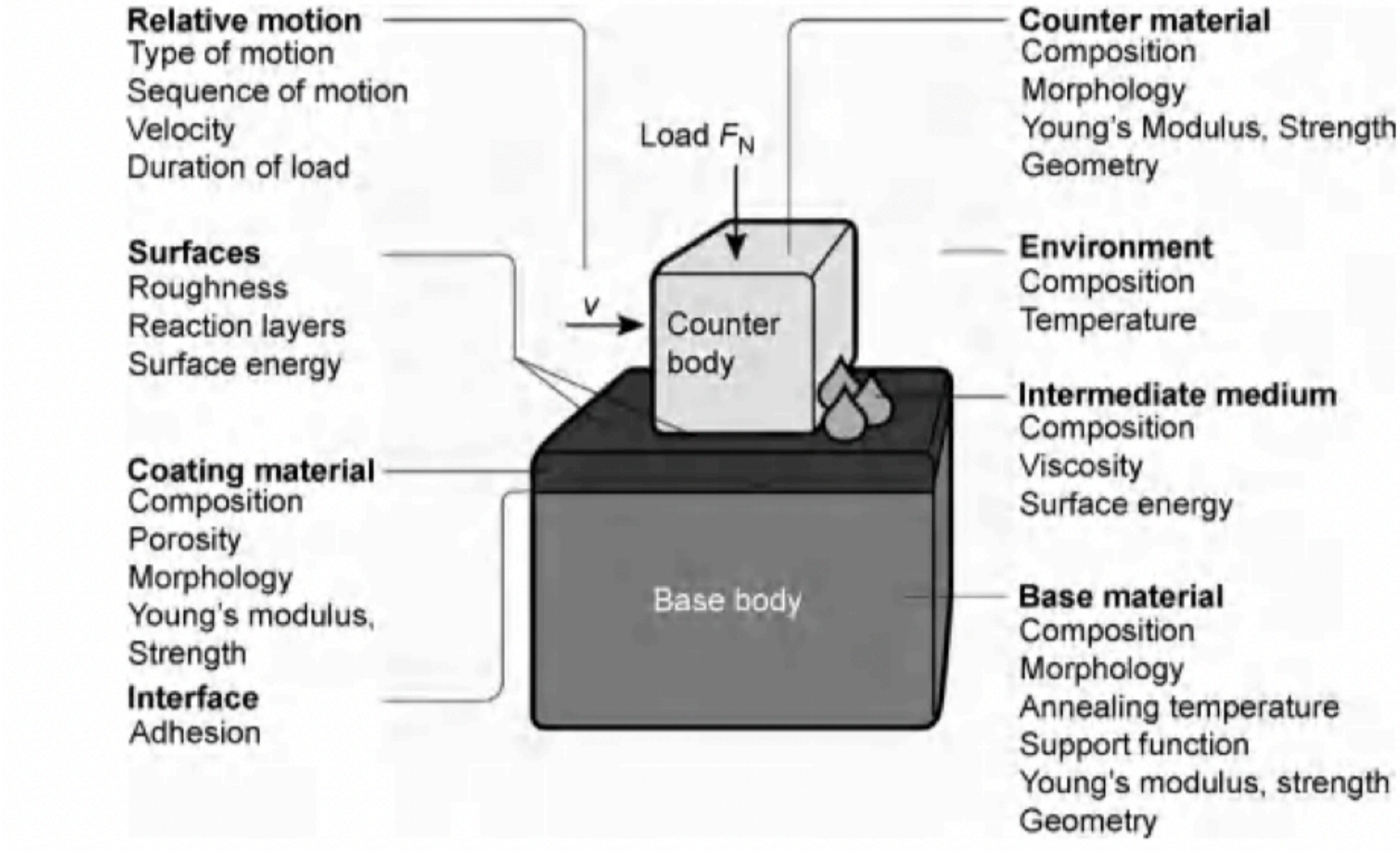


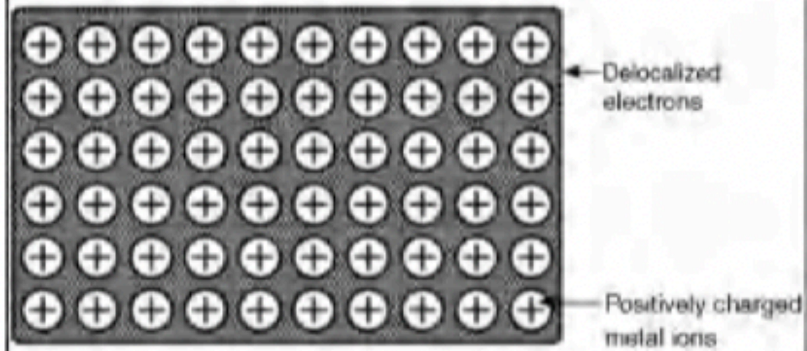
Figure 2: Variables governing a tribo system with coated base material.

TRIBOLOGICAL SURFACES

The chemical and physical phase boundary reactions on surfaces are based on atomic interactions. Each phase – which can be solid, liquid or gaseous – can be characterized in terms of its chemical composition, the acting bonding forces and its structure. The cohesion of the individual atoms within a phase is the result of chemical bonding, as shown in Figure 3.

A distinction can be made here between metallic bonding, ionic bonding, and covalent bonding (electron-pair bonding), with increasing bonding energy in this sequence. Much weaker bonding is found in the form of intermolecular bonding, which is responsible for the cohesion of molecules in a crystal lattice (e.g., solid carbon dioxide) or in a liquid (e.g., water).

Metallic bonding
Metal atoms lose their valence electrons to an electron gas, uniformly surrounding all metallic ions.
Examples: All metals and their alloys
- high electrical conductivity
- high thermal conductivity
- good plastic and elastic deformability
- high thermal expansion coefficient



Ionic bonding (heteropolar bonding)
An atom loses an electron to another atom, resulting in a noble gas configuration for both atoms. (F_A: Coulombforce)
Examples: Oxideceramics, sulfides, halogenides
- partly water-soluble (NaCl)

Oxide ceramics (Al_2O_3, ZrO_2):
- no electrical conductivity
- poor thermal conductivity
- hard, brittle
- high chemical stability

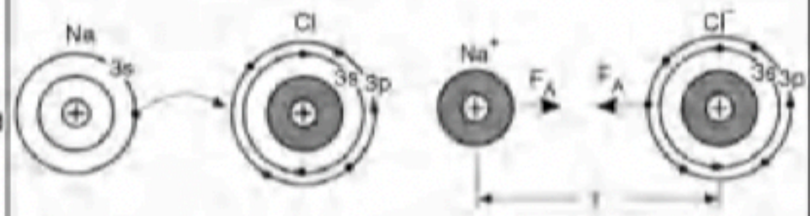
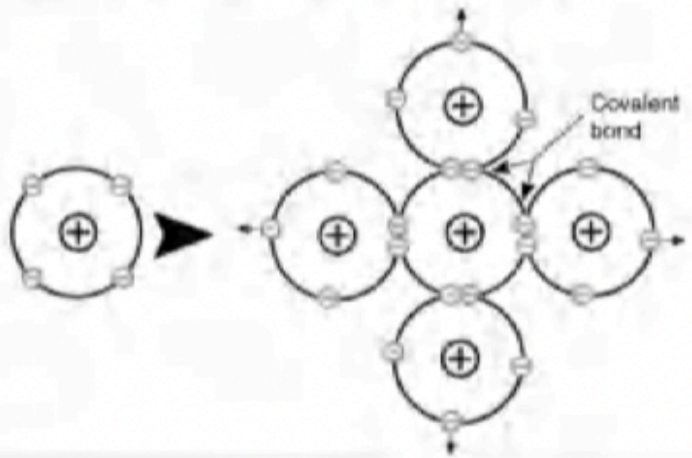


Figure 3: Structure and properties of atomic bonding types.

Covalent bonding (electron-pair binding)	Van der Waals bonding
Two atoms share their electrons, attaining a noble gas configuration. This permits restricted movement of the electrons.	Overlapping of molecular orbits and electrostatic interactions between permanent or temporary dipole molecules.
Examples: Diamond, silicon, boron carbide	**Examples:** Water, polymers, carbondioxide
▪ very hard, very brittle	▪ very low melting point
▪ low electrical conductivity	▪ very soft and elastic
▪ good high-temperature behavior	▪ very poor electrical conductors



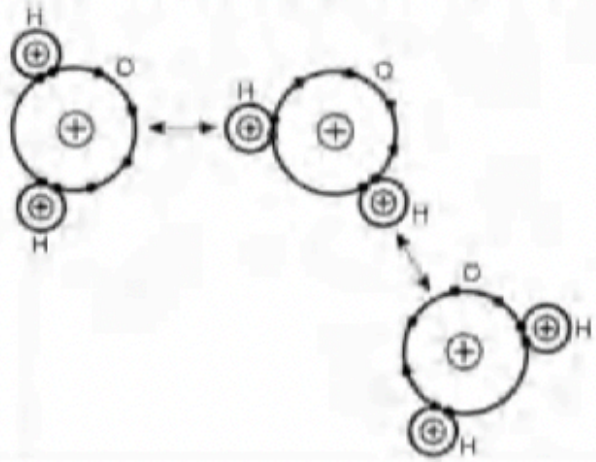


Figure 3: Structure and properties of atomic bonding types.

The microscopic form deviations are usually determined using a contact stylus, and described as "surface roughness values". The measurement procedures are standardized in accordance with DIN EN ISO 4287. The most frequently cited roughness values are in the form of the mean roughness depth Rz (Figure 4) and the mean roughness value Ra (Figure 5). These values are usually stated in micron or mm.

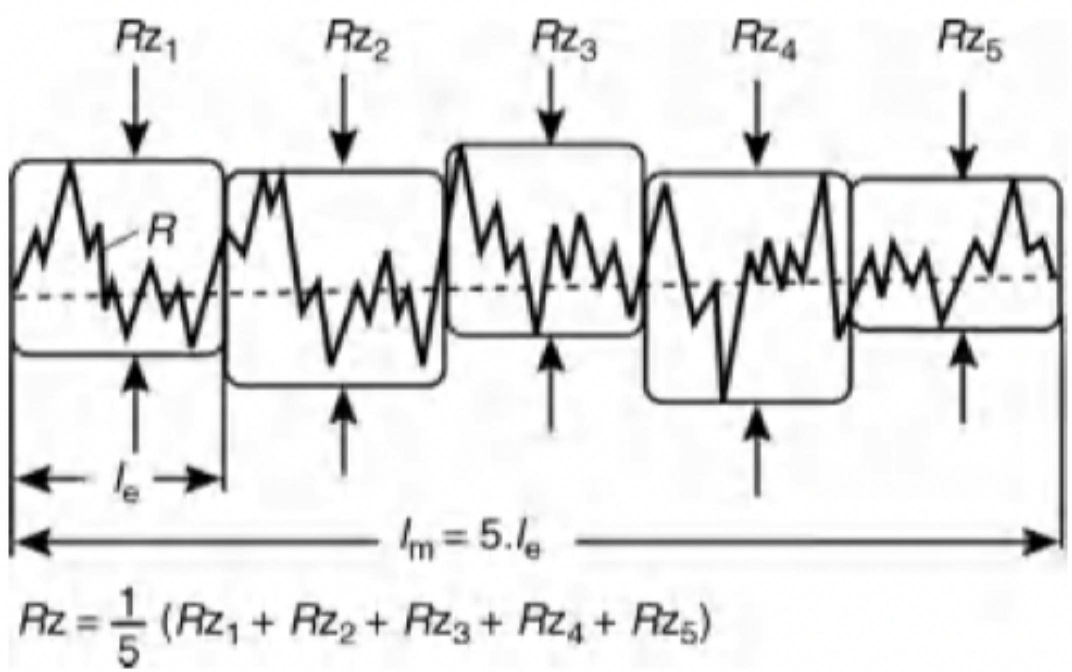


Figure 4: Mean roughness depth Rz: Mean value of the individual roughness depths (Rz1. . . Rz5) of five successive individual measurement segments *le* .

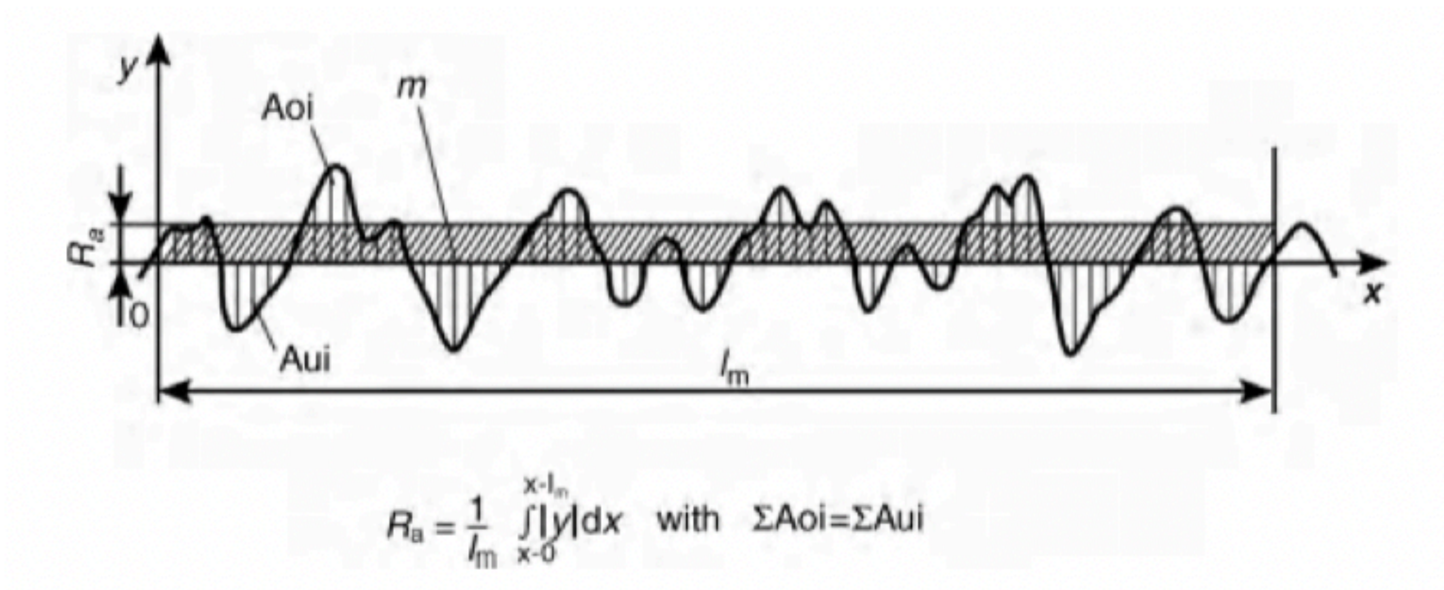


Figure 5: Mean roughness value Ra: Arithmetic mean of all deviations of the roughness profile R for the central reference line within the measurement segment *lm* .

In particular, due to the manufacturing process, the microstructure of material surfaces nearly always differs from that within the material.

For materials manufactured by the melting metallurgical process, the grain size in the edge zone of the component is frequently smaller. Mechanical loading during material processing results in plastic deformation of the boundary zones. As a result of strain hardening, the edge zone possesses a higher degree of hardness, as well as a greater yield strength and greater tensile strength.

Due to thermal loading, diffusion processes in the edge zone can lead to changes in the chemical composition, solidification effects, and/or re-crystallization effects. The internal stress situation in the edge zone, particularly with metallic substances, can in part considerably deviate from the value within the material.

In summary, it can be said that the edge zone of tribological surfaces is built up of several boundary layers, as shown in Figure 6. The strength properties, residual stress situation and chemical composition of these boundary layers will decisively influence the tribological properties of a solid body.

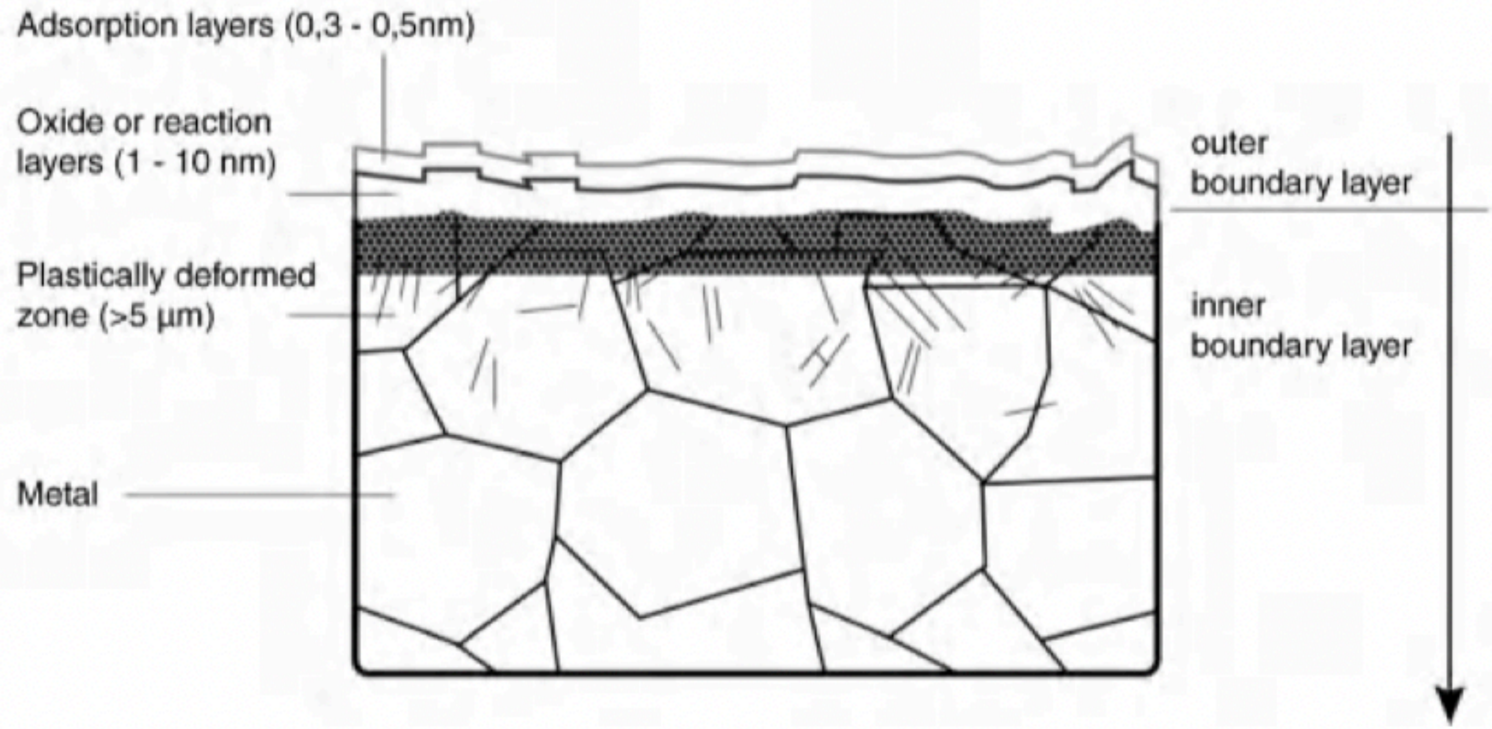


Figure 6: Structure of a metallic surface.

WETTING OF SOLID SURFACES

When two condensed phases come into contact, the interactions between the two phases reaching into the boundary layers determine the geometric form of the phase boundary. This becomes particularly apparent for contact between a liquid and a solid.

Here, a liquid droplet is initially subjected only to external gravitational effects and deformed, according to the prevailing intermolecular forces of adhesion (Van der Waals forces) in the solid body. The size of the boundary surface and the geometric form of the liquid surface are determined by the condition that the free energy of the entire system must be a minimum. From the form of a liquid droplet, conclusions can therefore be drawn concerning the type and magnitude of forces of adhesion acting over the boundary surface.

The first and best known description of a state of wetting was given by T. Young, in the year 1805. Young’s equation describes the equilibrium of forces between the interfacial tensions at the three-phase boundary, as shown in Figure 7. This determines the contact angle b, as a measure of wetting, from the material properties of the participating phases.

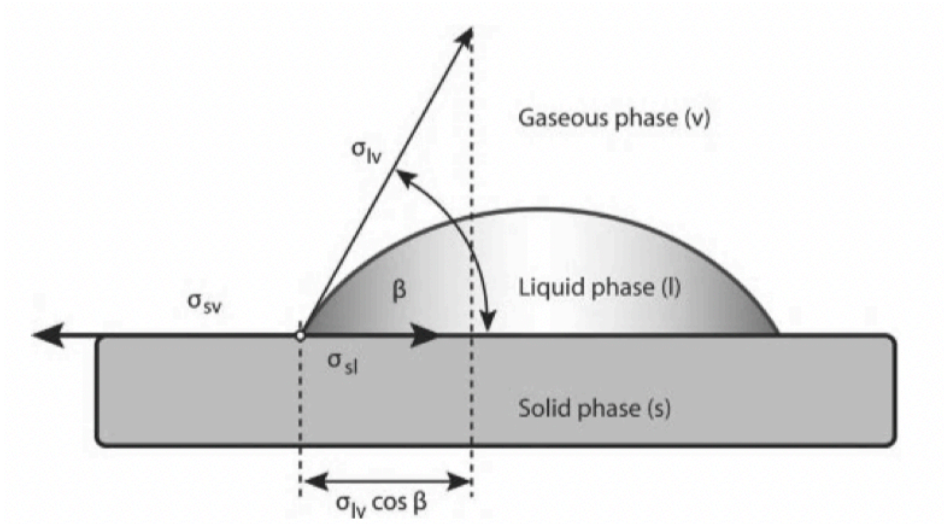


Figure 7: Tension relationships at the three-phase boundary acting on a liquid droplet.

Young’s equation:

$$\sigma_{sv} = \sigma_{sl} + \sigma_{lv} \cdot \cos\theta$$

Where;

β	: Contact angle
σ_{sv}	: solid–vapor surface tension
σ_{sl}	: solid–liquid interfacial tension
σ_{lv}	: liquid–vapor surface tension

TRIBO CONTACT SURFACES

The tribo contact surface describes the contact area between bodies in contact, in which the tribological loading is effective. The surface pressure, p, is given by the ratio of the normal force F_N to the tribo contact area A.

$$p = \frac{F_N}{A}$$

Due to the microgeometry of technical surfaces, the contact between two tribo bodies is restricted to discrete microcontacts, which deform under the influence of the normal force. In accordance with Figure 8, it is therefore necessary to distinguish between the geometric and nominal contact area A_0 and the (usually vastly smaller) real contact area A_r – that is, the area given by the sum of the microcontact surfaces. The real contact area is of central importance for all tribotechnical systems, as the frictional and wear processes take place primarily here.

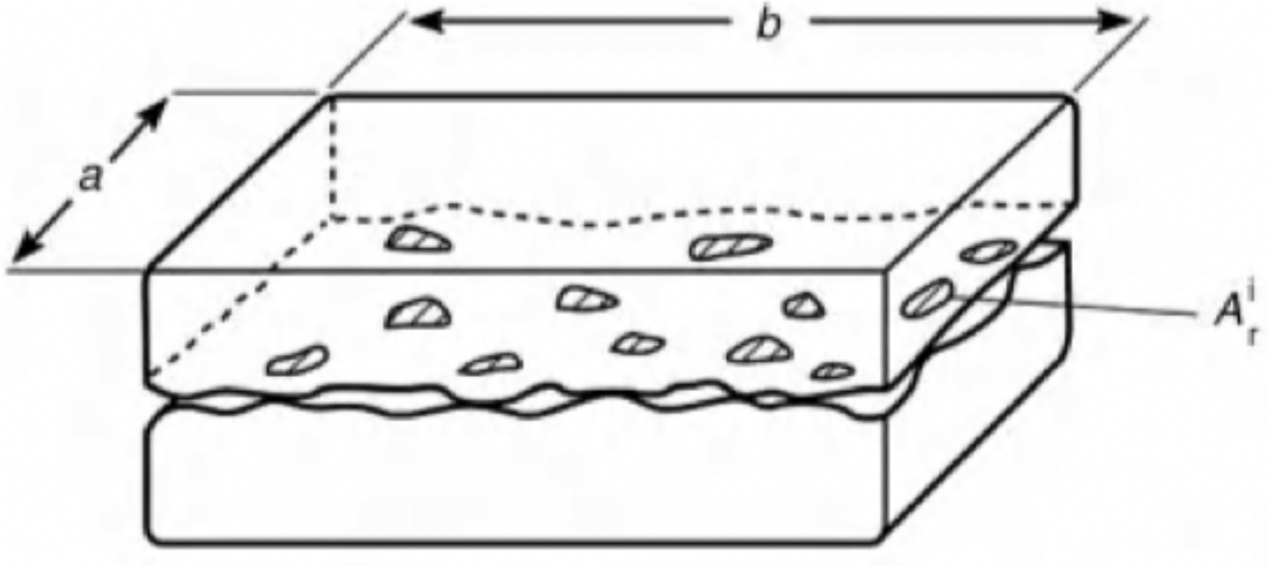


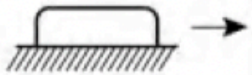
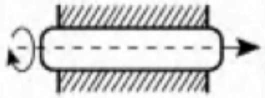
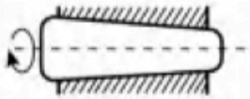
Figure 8: Geometric contact area A_0 and real contact area A_r at roughness peaks.

$$A_0 = a \times b \gg A_r$$

$$A_r = \sum_{i=1}^{n} A_r^i$$

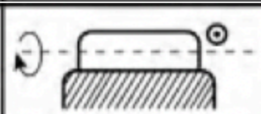
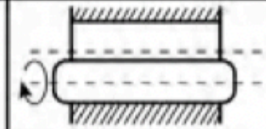
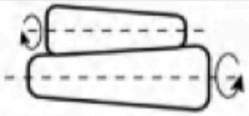
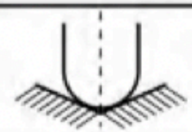
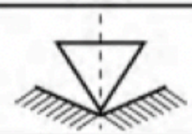
n = number of microcontacts

The macroscopic contact between the tribo bodies is determined by the construction. Here, it is possible to distinguish between conform contact forms, leading to surface contact, and contra-form contact forms, which are in turn further divided into linear and punctiform contacts. The most important forms of contact for closed tribo systems are summarized in Figure 9.

Contact shape		Area of Base body I	Area of Counter–body II	Sketch	Application examples
Conform	Surface contact	Plane	Plane		Straight-line motion
		Hollow cylinder	Full cylinder		Plain bearing, cylindrical fits, cylinder slight ways
		Hollow cone	Full cone		Bearing, conical fits

$d_I \approx d_{II}$

Conformal contacts fit into each other with a high degree of geometrical conformity so that the load is carried over a large area. Non-conformal contacts have surfaces that do not conform to each other. In these contacts the load is carried by a small area.

Contact shape		Area of		Sketch	Application examples
		Base body I	Counter-body II		
Contra-Conform or Non-conform	Line contact	Plane	Cylinder		Roller guides
		Hollow cylinder	Full cylinder		Needle bearings
		$d_I \gg d_{II}$			
		Full cylinder	Full cylinder		Roller mills, roller bearings
		$d_I \lessgtr d_{II}$			
		Full cone	Full cone		Conical friction wheel gearing
		Hollow cone	Ball calotte		Toe bearing
		Full prism	V-prism		Knife-edge bearing
		Involute surface	Involute surface		Gearwheel

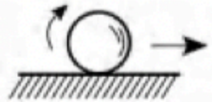
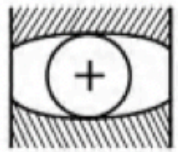
Contact shape		Area of Base body I	Area of Counter–body II	Sketch	Application examples
Contra-Conform or Non-conform	Point contatc	Plane	Ball		Ball guides
		Hollow cylinder	Ball		Ball guides
		Full cylinder	Ball		Ball guides
		Inner ring surface	Ball		Rolling bearings
		Outer ring surface	Ball		

Figure 9: Construction-conditioned contact geometries of tribological systems.

TRIBOLOGICAL LOADING

The relative motion of two bodies with surface contact leads to friction. Besides the relative motion, physical and chemical interactions between the surfaces induced by the presence of forces characterize the tribological loading as shown in Figure10.

Over the duration of loading, and as a result of these interactions, the tribo system continuously changes. The rate of the ongoing reactions on the surface of the material depends strongly upon the pressures (pressing) and temperatures arising.

Mechanical material failure depends, furthermore, on the form of motion and the loading over time (dynamic or static) and the related application of forces.

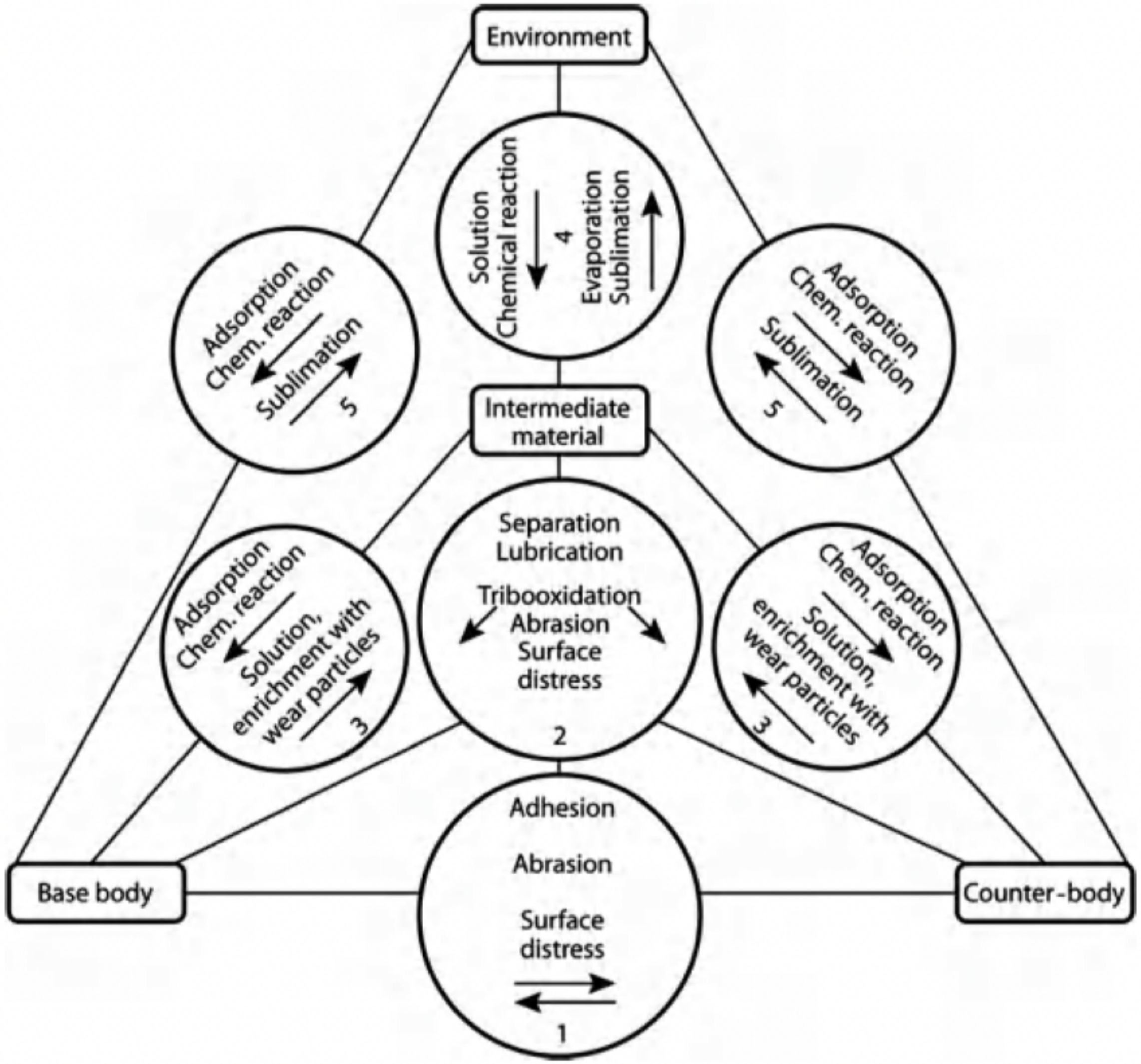


Figure 10: Possible interactions between the elements of a tribo system.

In accordance with the Society for Tribology, the complex of loads is comprised of:

1) The form of motion
2) The behavior over time
3) The physical-technical loading parameters

The **form of motion** which includes the four “elementary forms of motion” as well as the superposition of these:

1) Gliding: Including the form of motion “drilling’ in which the surface elements move in the contact area with different relative velocities

2) Rolling without slip: This always refers to the microscopic sliding part (micro-slippage). When macroscopic sliding parts (macro-slippage) simultaneously occur, we speak of “rolling with slip”.

3) Impact: As a synonym for the term “impact”, the term “collision” is frequently used.

4) Flowing: The term “flowing” corresponds to the term “gliding” for the case that the counter-body is a grained, liquid, or gaseous material.

The **behavior over time**

(1) Continuous

(2) Oscillating

(3) Intermittent.

The **physical-technical loading** parameters which include:

(1) The normal force, F_N : On the basis of the normal force F_N , knowledge of the size of the geometric contact area allows us to calculate the mean surface pressure, p . In addition, knowledge of the geometric dimensions of the components, the Young’s modulus of the materials used, and the coefficients of friction allow us to determine the material strain.

(2) Velocity, v: The decisive velocity v for wear processes is the “relative velocity” between the two wear partners.

(3) Temperature, T: This refers to the respective state of thermal equilibrium of the entire tribo system. For states of thermal nonequilibrium, for example, with different temperatures of the base material and counterbody, the introduction of several temperatures or temperature functions may be necessary.

(4) Load duration, t_B : This describes the length of time during which the tribological loading causing wear remains in effect. From knowledge of the load duration t_B and the velocity v, the loading path can be calculated.