Tribo Fracture-basic Concepts and Phenomena

O. VINGSBO
Uppsala University, School of Engineering, Dept. of Technology, Box 534, S-751 21 Uppsala, Sweden and University of Houston, Dept. of Mechanical Engineering, Houston, TX 77204-4792, USA

TRIBOLOGY - BACKGROUND AND DEFINITIONS

The word TRIBOLOGY was coined in England in the mid 60's, mainly as a common frame for the three related subjects of FRICTION, LUBRICATION and WEAR [1]. Gradually, the meaning has been generalized to comprise THE SCIENCE AND TECHNOLOGY OF INTERACTING SURFACES IN RELATIVE MOTION. Tribology still is a young discipline, and the terminology is not yet fully established. The present survey will be based on the following basic definitions, which are gaining acceptance among today's tribologists.

- TRIBO SURFACES: Surfaces in mechanical contact under relative motion.
- TRIBO SYSTEM: Any system comprising tribo surfaces.
- TRIBOLOGY: The science and technology of tribo systems.
- FRICTION: Force, acting against the relative sliding of tribo surfaces.
- WEAR: Loss of material from a tribo surface.
- FRICTION MECHANISM: Micromechanism by which friction takes place.
- WEAR MECHANISM: Micromechanism by which wear takes place.

TRIBO SURFACES

As indicated by the definition, the key issue in Tribology is the mechanical contact between tribo surfaces. Tribology generally refers to engineering surfaces, with the two main characteristics that previous handling and treatment (machining, grinding, heating, forming, etc.) in an atmosphere results in the development of i) a surface topography, and ii) a subsurface layer of a varying thickness, which is modified with respect to the virgin material as to microstructure and chemical composition.

The mechanical contact between two tribo surfaces, which are pressed together by a normal load L_o, is established only at scattered, protruding surface elements at the summits of asperities, defining area elements A_i of real contact, each carrying its part L_i of the normal load (Fig. 1a, b). The effect of the topography is that the sum of all contact area elements - the real contact area A - is, in a general case, considerably smaller than the apparent (or nominal) contact area A_o, according to

$$A = \Sigma A_i << A_o \qquad (1)$$

Consequently, the real contact pressure p is higher than the nominal contact pressure p_o, which is the quantity generally (and implicitly) used in Solid Mechanics, according to

$$p = \Sigma L_i / \Sigma A_i = L_o/A \gg L_o/A_o = p_o \qquad (2)$$

This is a basic difference between Tribology and Solid Mechanics, and, in fact, a reason why continuum elasticity generally is a poor approximation in friction and wear models.

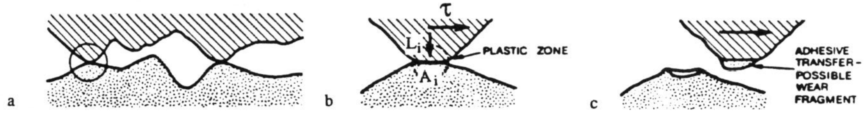

Fig. 1 Schematic representation of asperity contact between engineering surfaces.

SLIDING CONTACT

In addition to normal force components, a general tribo system includes tangential force components T, which may cause relative sliding between the tribo surfaces. The action of tangential forces, with or without sliding, also causes a growth of the real contact area by plastic deformation of each asperity contact (in ductile materials).

Continuum mechanical treatments of sliding contact are based on an implicitly postulated friction force F = -T, that is proportional to the normal load, according to the Law of Friction

$$-F = T = \mu \cdot L_o \qquad (3)$$

Tribology studies, however, aimed at understanding the phenomena of friction and wear, emphasize the physical mechanisms of sliding surface contact, taking the action of interatomic forces across the interface into account. This is a central goal of Tribology research, and much work has been devoted to the development of friction and wear theories. Nevertheless, the original Asperity Junction Model, worked out by Bowden and Tabor [2] in the 1940's, still is the basis of our fundamental understanding. The starting point of the model is the formation, at a surface element of real contact, of interatomic bonds extended from one of the mating surface elements into the other. The previous elements of external surface are transformed into elements of interface, for example a grain boundary, forming an asperity junction. Irrespective of the nature of the bond, it takes mechanical work to break it up. During sliding new junctions are continuously formed and sheared off, and the consumed work, the friction work, is provided by the tangential force T. The corresponding shear stress (Fig. 1b)

$$\tau = T/A \geq s \qquad (4)$$

has to match the shear strength s of the junction, and the friction force F is given by

$$-F = s \cdot A \qquad (5)$$

Substitution of (2) gives the load dependence (the opposite directions of T and F are generally neglected by dropping the negative sign)

$$F = s/p \cdot L_o = \mu \cdot L_o \qquad (6)$$

in agreement with the Law of Friction. (6) defines the coefficient of friction μ as the ratio between the shear strength s and the normal flow stress p of the asperity junction.

The simple asperity junction model does not explicitly describe more complex phenomena like plowing, influence of velocity and temperature, or stick-slip, but it explains the most fundamental mechanisms in friction and wear.

FRICTION, WEAR AND TRIBO FRACTURE

If the shear fracture process, by which the asperity junction is sheared off according to the Asperity Junction Model, takes place in the original contact interface of the junction, neither of the tribo surfaces suffer a net loss of material. Eq. (6) then describes a case of pure friction. If, on the contrary, the shear fracture take place along any other surface, that happens to be weaker than the original interface, the net effect is that material is transported from one of the tribo surfaces to the other. This means a loss of material from one of the surfaces, and by definition wear has occurred (Fig. 1c).

In both cases, whether friction or wear dominates, a necessary mechanism of surface interaction is fracture. Referring to the introductory set of basic definitions, Tribology deals with micromechanisms, restricted to thin surface layers, as compared to the type of bulk fracture that defines catastrophic failure. The fracture events in Tribology are referred to as Tribo Fracture mechanisms. The Asperity Junction Model gives the background of so called adhesive friction and wear models. There are a number of other tribo fracture mechanisms, and in practice two or more tribo fracture mechanisms usually interact. In addition, a general tribo system also involves a variety of interactive mechanisms, such as plastic deformation, heating, diffusion, corrosion, etc., that are not tribo characteristic as such, but contribute effectively to the deterioration of the system [3].

The combined effects of tribo fracture and interactive mechanisms are described in the literature in terms of "wear mechanisms", the number and complexity of which tends to grow to impracticable levels. The number of different tribo fracture mechanisms that have been suggested and described, however, is very limited. In a strict sense, there are only four basic tribo fracture mechanisms, defined in TABLE I below, and described in some detail in the next chapter.

The first two of the tribo fracture mechanisms are closely related to the asperity junction and the plowing friction mechanisms, whereas the latter two are less exclusively tribo characteristic. It can be argued that contact fatigue, which is included here, is not a definable mechanism, and thus should be excluded, leaving only three basic mechanisms. On the other hand, it has also been argued that mechanisms of, for example, plucking atoms one by one from a tribo surface

TABLE I

Loading Mode	Tribo fracture mechanism
Tangential	Shear of asperity junctions Micro cutting
Transient normal stress	Impact microfracture
Oscillating stress	Surface contact fatigue

ought to be included. Additional tribo fracture mechanisms may be suggested mainly depending on the degree of specialization of tribo system that is considered. The total number of possible mechanisms, though, will always be very limited.

SHEAR OF ASPERITY JUNCTIONS

During sliding between tribo surfaces existing asperity junctions are subjected to shear deformation and, eventually, fracture. In the asperity junction theory of friction it was assumed that shear fracture took place exactly along the interface of the junction. Strain hardening of the shear zone may, however, increase the probability of the fracture to occur in softer material within one of the asperities, at a distance from the interface, as demonstrated by Fig. 1c. During repeated transport back and forth, the transferred volume may eventually be lost from the tribo system as a wear fragment. Depending on material and deformation characteristics the tribo fracture can take place by, for example, formation of "shear scales", by ductile necking, or by heavy plastic deformation, as shown in Fig. 2 a-c. Formation and shear of asperity junctions is a mechanism that is promoted by high ductility, in friction as well as in wear.

PLOWING MICROCUTTING

The basic mechanism of the plowing friction and wear component is the grooving action of a hard particle or edge in a softer surface. The prerequisites are that the grooving element:

- o has a higher hardness than the surface to be grooved.
- o is fixed with respect to rolling over the tribo surface. (If loose particles between two surfaces are to be effective as grooving elements, they must be embedded in one of the surfaces in order to groove the other.)
- o is sufficiently tough, or else it will break by brittle fracture at first contact.

The grooving action may imply the formation of a microchip by microcutting, which is the dominating tribo fracture mechanism in abrasive wear. A prerequisite is that the cutting tip or edge must have a suitable geometry and cutting angle, depending on the active normal and tangential force components. (Too blunt edges or too obtuse cutting angles will result in plowing without chip formation.)

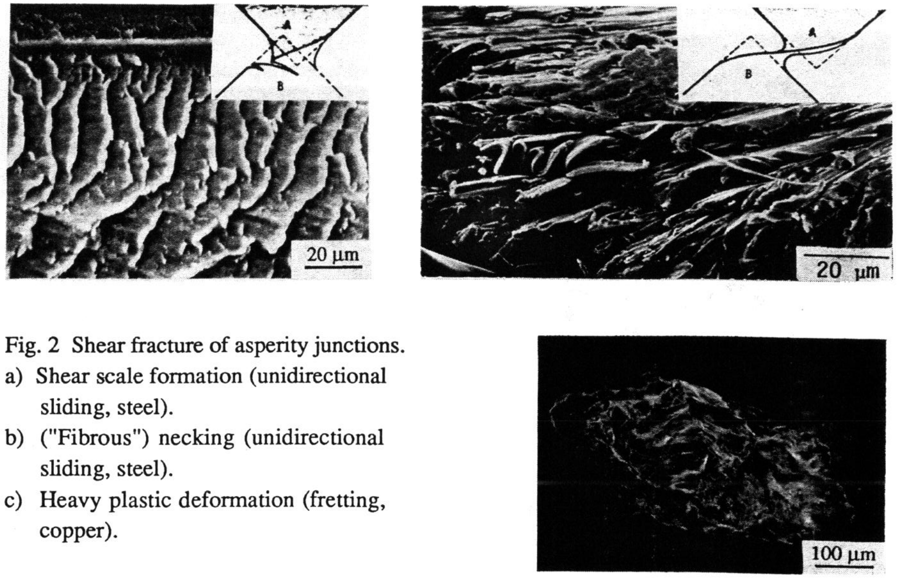

Fig. 2 Shear fracture of asperity junctions.
a) Shear scale formation (unidirectional sliding, steel).
b) ("Fibrous") necking (unidirectional sliding, steel).
c) Heavy plastic deformation (fretting, copper).

A scanning electron micrograph, showing microcutting and chip formation by a hard grain, sliding over a metal surface, is reproduced in Fig. 3. The microcutting mechanism in chip formation is similar to the bulk mechanisms in macroscale metal cutting. Depending on the grooving conditions, the morphology of the chip may vary from a homogeneously deformed to a fully developed lamellar microstructure (Fig. 4).

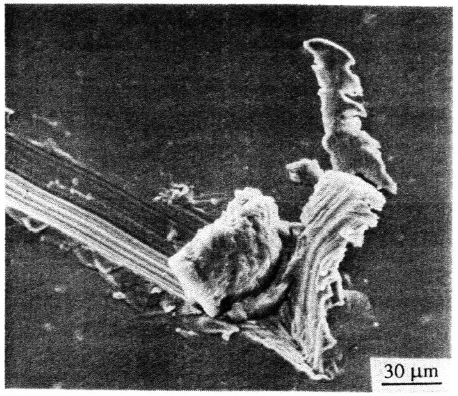

Fig. 3 The grooving action of a sand grain, sliding over a copper surface.

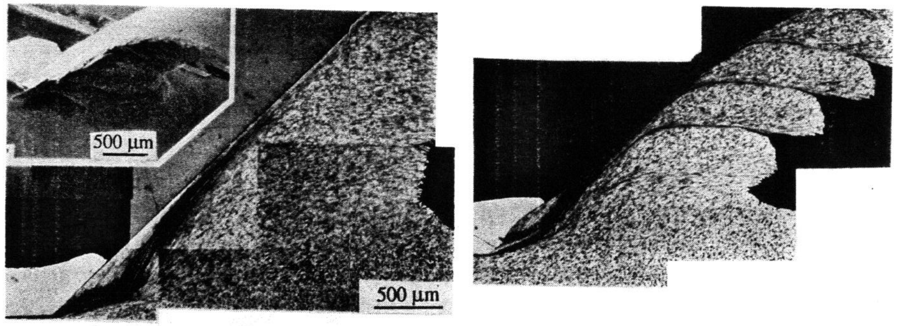

Fig. 4 Chip formation by single pass pendulum grooving of a pearlitic-ferritic steel [4]. Light optical micrographs of etched longitudinal cross sections through specimens with chips being extruded, and SEM micrograph of the chip.
a) Homogeneous chip formation.
b) Lamellar chip formation.

IMPACT

The transient process of applying a load when particles impinge on a surface, or when contact between two tribo surfaces is established under normal movement, implies that kinetic energy is transferred into the target area during the impact. The energy is dissipated as heat and plastic deformation. If plastic deformation is difficult (brittle material, or too high strain rates), fragments will be released from the surface, and the impact energy is transferred into fracture work (surface energy) and kinetic energy of the loose fragments. Characteristic conditions are a high contact pressure peak of short duration and high strain gradients (small target area). For decreasing impact angle, the normal component of the momentum decreases, and the probability of sliding contact will increase. An example of impact tribo fracture is shown in Fig. 5.

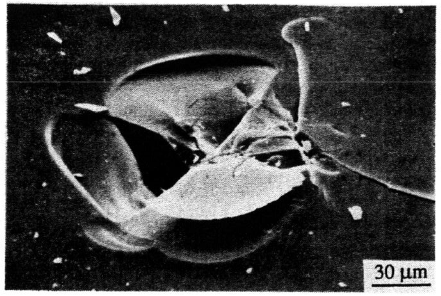

Fig. 5 Impact tribo fracture by normal percussion in glass surface.

SURFACE FATIGUE

Most tribo systems involve cyclic movements or repeated passages, and consequently surface fatigue phenomena are commonly observed on tribo surfaces. Both tangential and normal force components are of importance, i.e. sliding and rolling contact as well as impact may cause contact fatigue. As a matter of fact, load fluctuations are extremely common even in apparently non-cyclic events, such as unidirectional glide. A considered asperity, for example, can be subjected to repeated contact with a number of different elements in the mating tribo surface, depending on the surface roughness of the latter. As a consequence of the load fluctuations, micro cracks may be nucleated in or closely underneath the tribo surface. After successive growth, fatigue cracks may propagate in different planes into a pattern that releases fragments from the surface (delamination). Fig. 6 shows an example of tribo fracture fatigue close to the edge of a steel punch.

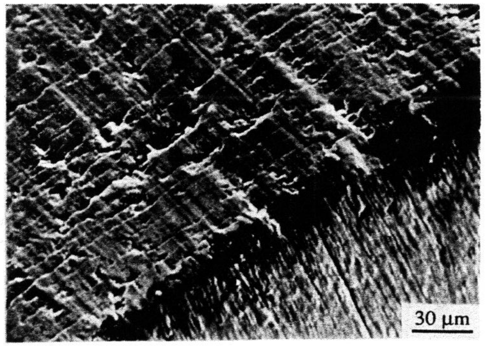

Fig. 6 Tribo fracture by contact fatigue of a steel punch.

INTERACTION BETWEEN DIFFERENT TRIBO FRACTURE MECHANISMS

A consequence of the complexity of a general tribo system is that the mechanical parameters rarely are so specialized that they generate only one mode of tribo fracture, and in practice a mixture of different interacting mechanisms generally operate simultaneously. For example, the bottom of a groove after microcutting may exhibit scales, typical of sheared asperity junctions (see Fig. 7). In particular, fluctuating loads are so common that surface fatigue is normally observed.

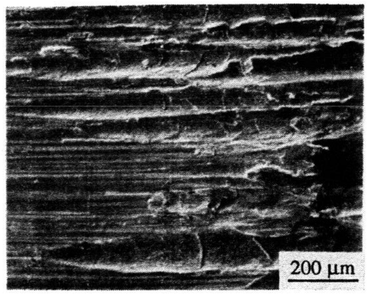

Fig. 7 Abrasive grooves with shear fracture scales (steel).

ACTIVE LAYERS

As soon as a Tribo System becomes active, the frictional work will inject energy into the tribo surfaces and affect a sub-surface layer, the material of which will be modified by the interactive mechanisms characteristic of the tribo system. The microstructure as well as the related properties of this so called active layer may deviate drastically from those of the unaffected virgin material [5]. An image example of a sub-surface layer in an excavator tooth (AISI 4337) is shown in the light optical micrograph of Fig. 8. The two white-etching layers correspond to untempered friction martensite, formed during two different abrasive events, and separated by a dark band of annealed material.

The properties of the tribo surfaces during sliding are, thus, controlled by the relevant parameters of the material in the active layers, rather than those of the virgin material. In calculations and estimates of fracturecontrolling quantities, therefore, it is of great importance to be aware of the errors introduced by applying, for instance, room temperature or "catalogue" values of parameters like hardness, fracture toughness, yield stress or strain and strain rate.

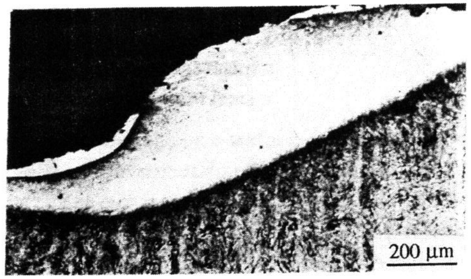

Fig. 8 Etched cross section through the sub-surface layer of an abraded excavator tooth.

REFERENCES

1. H.P. Jost, Lubrication (Tribology) - Eduction and Research, HMSO, London, 1966.
2. F.P. Bowden, D. Tabor, The Friction and Lubrication of Solids, Part I, Clarendon Press, Oxford, 1950.
3. O. Vingsbo, Wear and Wear Mechanisms, Wear of Materials 1979, ASME, New York, 1979, p. 620.
4. O. Vingsbo, S. Hogmark, Single-Pass Pendulum Grooving - A Technique of Abrasive Testing, Wear 100 (1984) 489.
5. O. Vingsbo, S. Hogmark, Wear of Steels, in D.A. Rigney (Ed.), Fundamentals of Friction and Wear of Materials, ASM, 1981, p. 373.