CHAPTER 2

Green Tribology

INNOVATIVE TECHNOLOGIES to reduce the greenhouse effect are termed "green" technologies. Green technologies deal with the subject of overall improvement in energy to negate global warming. Green tribology has become a key subject to improve energy efficiencies and conserve nonrenewable resources in a wide spectrum of industries. The tribological processes such as wear and friction lead to loss of material and energy from the interacting surfaces of components in equipment and machinery, making them energy inefficient and redundant at an early stage of life. Frequent replacement of the equipment leads to a huge waste of energy and material. The basic goals in green tribological efforts include reduction of material loss, reduction in energy loss, and life-cycle extension. Tribological aspects of these three basic objectives are discussed in this chapter.

History of Tribology and Green Tribology

The word *tribology* comes from the Greek term *tribos*, or rubbing. Tribology or triboscience is defined as the science of friction, wear, and lubrication of interacting surfaces in relative motion, involving energy dissipation and material loss (Ref 2.1).

Leonardo da Vinci (1452 to 1519) was the first to explain the two laws of friction. According to da Vinci, the frictional resistance is the same for two different objects of the same weight that make contact over areas with different widths and lengths. He also observed that the force needed to overcome friction is doubled when the weight is doubled. It took almost five centuries through early frictional studies by Amonton (1699) and Coulomb (1736 to 1820), followed by formulation of a wear equation by Archard (1953), to decipher da Vinci's codes on friction, wear, and lubrication (Ref 2.1).

The term *tribology* appeared for the first time in a United Kingdom Government Report published on March 9, 1966, now commonly known as the Jost report (Ref 2.2). According to the Jost report, tribology offers great opportunities for saving industries billions of dollars that they lose due to wear.

The term *green tribology* is defined by H.P. Jost as "the science and technology of the tribological aspects of ecological balance and of environmental and biological impacts" (Ref 2.3). Jost gave credit for coining the term *green tribology* to Professor Si-Wei Zhang of China, who "launched (green tribology) as a tribology policy in London on June 8, 2009, which date can be regarded as the acknowledged birthday of green tribology as an international concept" (Ref 2.4). Green tribology is also known as ecotribology. Since its inception, green tribology has been a key subject in major international and world tribology conferences (Ref 2.5, 2.6).

According to Hill and Kassebaum of the Institute of Electrical and Electronics Engineers, green or environmentally-friendly tribology emphasizes those aspects of interacting surfaces in relative motion that are of importance for energy conservation and conversion with respect to environmental sustainability and that have a major impact on the concurrent environmental problems of global warming (Ref 2.7).

Basic science has taught us that energy cannot be created nor destroyed but can be transformed from one type to another. Energy transformation from one form to another is always accompanied by dissipation of some energy in another form. Tribological processes, such as friction and wear, are accompanied by energy dissipation and material loss from the surfaces of interacting materials. The efficiency of the transformation or transfer process is therefore limited in value, depending on the extent of energy dissipation.

According to a recent report (Ref 2.8), green engineering plays an important role in reducing greenhouse effects. Green engineering efforts to reduce emissions include technologies to improve efficiencies in energy conversion, consumption, and conservation processes. According to Nosonivsky and Bhushan (Ref 2.9), tribological research to improve efficiencies in energy should achieve:

- Reduction of material and energy loss due to wear
- Reduction in energy loss due to friction
- Conservation of energy and nonrenewable resources by extending life cycles of the components
- Reduction or elimination of lubricants by proper selection of low-friction mating surfaces

Green tribology deals with the subject of overall improvement in energy to negate global warming. Tribological studies have effectively reduced wear, friction, and the use of lubrication of the interacting surfaces in relative motion, leading to efficient functioning of these and other interacting components in energy-related processes.

The progressive loss of material from the surface of interacting components by wear leads to a gradual loss in efficiency, followed by premature failure of the component, thus considerably reducing the life cycle. The scrapping of an engineered component made from nonrenewable resources at an early stage in life due to wear goes against the ethics of the conservation of natural resources. Lower life span may also result from more strained materials because friction leads to an expedited aging process (Ref 2.10). Extension of the life cycle by reducing wear and friction leads to conservation of nonrenewable resources and a sustainable environment.

Economic and Energy Loss due to Wear and Friction

A large amount of energy is lost due to friction. In a diesel engine, only a maximum of 30% of the fuel is directly transformed into driving energy. According to different estimations, friction and wear of material cause an economic loss of 5 to 8% of the gross domestic product each year in Germany (Ref 2.10).

The direct and consequential annual loss due to wear and corrosion in the United States is $500 billion (Ref 2.1). The tribology surveys conducted by the Department of Energy, along with the Energy Conversion and Utilization Technology Program, indicate that the estimated direct and indirect losses of energy caused by simple wear and friction in 1978 is over 4 quadrillion Btu in the United States. Assuming an average growth rate of 3 to 5% per year in all of the industrial sectors, the proportional increase in energy loss by material degradation (3 to 5% per year compounded for 32 years, from 1978 to 2010) is in the range of 10.4 to 18.4 quadrillion Btu in the United States.

According to the survey, steps to reduce energy loss include (Ref 2.11):

- Identification of typical tribology energy sinks in industry
- Reduction of tribological losses in major sinks such as utilities and transportation
- Exploitation of the energy conservation potential of new surface modifications

In the United States, it is estimated that approximately 11% of total energy can be saved in major areas of transportation, turbomachinery, power generation, and industrial processes through progress in tribology (Ref 2.12). Tribological improvements in cars alone can save 18.6% of the total annual energy consumed by cars in the United States, which is equivalent to approximately 14.3 billion U.S. dollars per annum (Ref 2.11).

The total cost of wear for a single U.S. naval aircraft is estimated to be $243 per flight hour (Ref 2.13).

Wear of Material

Wear is defined as the loss of material from a mating surface due to tribological interaction in relative motion. The definition of wear does not include loss of dimension from plastic deformation, although wear has occurred despite no material removal. This definition also fails to include impact wear, where there is no sliding motion or cavitation, or where the counterbody is a fluid and corrosion damage is due to chemical rather than mechanical action (Ref 2.1).

Wear is caused by interactions of solid surfaces with counterbodies and the surrounding environment. The wear environment or system envelope causing wear is defined in DIN 50320. In accordance with DIN 50320, wear is not an intrinsic property of the material but a system property.

The performance of the material therefore depends on the wear system or system envelope (Fig. 2.1). In a given system envelope, which is determined by the boundary conditions of the system, wear occurs only when the following conditions are satisfied:

- A wear-causing counterbody or countermaterial ("1" in Fig. 2.1) is in contact with the base material ("3") or with the interposition of an intermediate material ("2") of similar or dissimilar nature. The combination can be referred to as wear mating.
- A relative movement ("5" in Fig. 2.1) exists between the wear mating components under load. The movement and the load factors together are referred to as the primary actions. The extent of wear therefore depends primarily on the applied load and the sliding distance under the load.

Three important aspects governing the wear behavior of materials include:

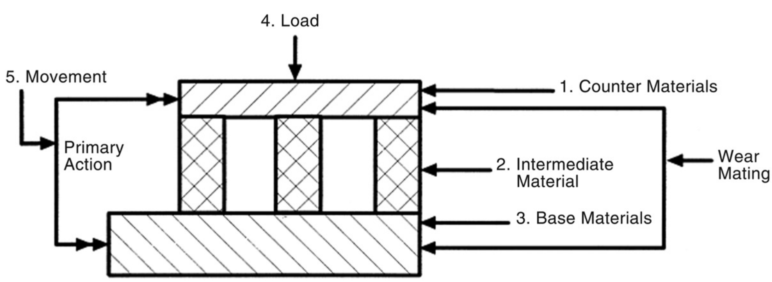

Fig. 2.1 Wear system (DIN 50320). Source: Ref 2.1

- Wear is surface-specific. The nature and extent of wear depends on the surface properties rather than the bulk material. The properties of surfaces are usually different from bulk properties. Surface properties govern the tribological characteristics and thus the wear behavior of a solid. The main surface properties responsible for controlling wear of materials include energy, microstructure, roughness, hardness, and composition. Modification of these surface properties alters the quantum of wear from the surface. Surface modification creates new surfaces with properties different from the original surface. Due to changes in surface properties, the wear rate and mechanism change with the progress of wear.
- Primary action controls the quantum of wear. The primary action (load and sliding distance) is the input energy at which the counterbody interacts with the solid surface. The wear rate is a function of energy input. Wear is the process of energy transfer and conversion from the wear-causing countermaterial to the mating surface. Thus, an extremely hard diamond tool as countermaterial cannot outperform the metal-removal speed of a high-pressure water jet or high-energy flame, plasma, or laser jet. Extremely high energy impact supersedes the wear rates of ultrahard countermaterial. Wear is therefore an energy-driven process.
- Wear is environment-specific. Aspects of the working environment that affect wear include load and types of loading (such as unidirectional sliding, reciprocating, rolling, vibratory, and impact), speed, temperature, type of counterbody (solid, liquid, or gas and their reactivity with the component surface), and type of contact (single phase or multiphase, in which the phases involved are liquid or solid particles or gas bubbles). The severity of the environment defines the extent of wear of a given solid surface.

A simple classification system based on different types of interacting wear environments is given in Table 2.1. The counterbody may be a solid surface (resulting in adhesive wear), abrasive particle (causing abrasive

Table 2.1 Classification of types of wear based on environmental interactions

Type/mode	Interacting environment	Control
Adhesive	Similar or dissimilar material	Alter surface properties; lubrication
Abrasive	Solid particles	Alter surface properties
Erosive	Suspended particles in fluid media	Change particle impingement angle by use of buffer plate or change in design; alter surface properties
Corrosive	Reactive fluids	Alter surface properties; electrochemical methods
Cavitation	Collapsing of bubble carried in liquid on surface	Alter surface properties
Thermal	Heat	Alter surface properties; insulate the surface (e.g., by thermal barrier coating)
Fatigue	Alternative/cyclic stress	Avoid local stresses; alter surface properties including residual stresses at surface

Source: Ref 2.1

wear), suspended particle in fluid media (resulting in erosive wear), reactive fluid (causing corrosive wear), heat (resulting in thermal wear), stress cycle (surface fatigue), or a combination of two or more types of wear, such as corrosion-erosion.

The list of types of wear is incomplete due to a large number of factors affecting the wear process. The type of primary action and the nature of wear mating can be considered important factors in classifying different types of wear.

Blau used a classification system based on wear due to different mechanical wear processes (Ref 2.14), thermal wear (by heat), and corrosive wear (oxidation, diffusion).

Wear Equation

The general form of the wear equation is based on the relationship developed by Archard (Ref 2.15). The wear volume (V) is directly proportional to the sliding distance (d) and the applied normal force (F_n) and inversely proportional to the hardness or yield stress (H) of the softer surface:

$$V = K\frac{F_n}{H}\cdot d \qquad \text{(Eq 2.1)}$$

The depth of wear (δ) is expressed as:

$$\delta = K\frac{F_n}{H}\cdot\frac{d}{A} \qquad \text{(Eq 2.2)}$$

where A is the area of contact, $V \approx \delta A$, and K is the wear coefficient.

The wear coefficient K is a proportionality constant number; K becomes equal to the wear volume per unit sliding distance when the applied normal force is equal to the hardness ($F_n = H$) or yield stress of the softer material. The wear coefficient K can be determined for a wear system from laboratory tests or field data.

Hardness of the Material. Hardness is the only material property included in the wear equation. The indentation load for hardness determination is selected according to the expected hardness of the material, so that the penetration of the indenter is limited to the near-surface region. Indentation hardness therefore indicates the hardness of the surface or near-surface region. The bulk of the material may or may not have the same hardness as that of the surface. The wear of material depends on the surface hardness of the solid.

The surface hardness of material is also related to the binding energy and thus the surface energy, yield, or flow stress of ductile solids and the fracture toughness (K_{Ic}) of brittle materials.

Wear Volume. Wear is normally measured as the loss of material in volume from the surface(s) interfacing with the working environment (Eq 2.1). For a worn surface, the depth of wear (δ) is a measure of the dimensional loss of the working face of the component. The dimensional loss in the working surface of the component beyond a tolerance limit causes the equipment or machinery to malfunction. Malfunctioning is associated with higher energy loss and premature failure. The rapid dimensional loss due to the severity of the wear process makes the life span of the equipment or machinery shorter than the designed life.

Material loss in terms of volume is directly related to the normal force and sliding distance and inversely to hardness. There is a progressive increase in wear with sliding distance and thus also with time.

Wear Life. The wear rate can be high or low at the initial or run-in wear stage, followed by a steady wear-rate state and ending high in the final stage, leading to failure. The duration or time span of the steady wear state defines the working life of engineering components. With increasing severity in the environment, the time span of the secondary or steady stage decreases. In extreme cases, this leads to merger of the initial to final state, thus drastically cutting down the wear life. Wear rate is normally defined as the volume loss due to wear per unit sliding distance.

Energy Loss in Wear. The energy required to remove material from the surface is considered the dissipation or loss of energy. The loss in energy is proportional to the volume loss at a given hardness.

Estimation of Energy Loss. Methods of energy-loss estimation follow.

Energy Loss from Hardness and Wear Volume. The Vickers hardness of the material is expressed as:

$$\text{Hardness in Vickers pyramid number (VPN)} = 2P\sin(\alpha/2)/d^2 = 1.8544P/d^2 = H \quad \text{(Eq 2.3)}$$

A diamond indenter of angle α is used to produce an indent of area d (mm^2) on the surface of the material by an applied load, P (kilogram force, or kgf).

Hardness (H) in VPN is expressed in kgf/mm^2 and is considered as the force required to produce an indent of unit area on the surface. Repetitive indentations by hard particles result in wear of material from the surface.

In Archard's equation (Eq 2.1), if $F_n = H$, then $V/d = K$. The wear coefficient K of a material is equal to the wear volume (V) per unit sliding distance ($d = 1$) when the applied normal force (F_n) becomes equal to the hardness of the material (H). In other words, the applied force needed to remove K quantity of material for unit sliding distance is equal to the hardness of the material.

For removal of K (wear coefficient), materials with hardness values of 392 VPN (equal to a pressure of 1455 MPa, or 211 ksi, in accordance with

Eq 2.3) and 674 VPN (equal to a pressure of 2503 MPa, or 363 ksi, in accordance with Eq 2.3) require approximately applied pressures of 1455 and 2503 MPa (211 and 363 ksi), respectively.

Energy is expressed as (Ref 2.16):

$$\begin{aligned}
\text{Energy } (E) &= \text{Force } (F) \times \text{distance } (d) \\
\text{Pressure } (P) &= F/A = F/d^2\text{; Volume} = d^3 \\
\text{Energy } (E) &= \text{Pressure } (P) \times \text{Volume } (V) = F \cdot d \\
&= \text{Volume } (V) \times \text{Hardness } (H) \\
&= V\,(1.8544P/d^2) \\
&= K_{abr} \cdot F_n \cdot d
\end{aligned} \qquad \text{(Eq 2.4)}$$

where K_{abr} is the wear coefficient for abrasive wear.

In the standard test condition of ASTM G65, practice A, the applied load (F_n) against the specimen is fixed at 130 N (29.2 lb) as well as d, the linear distance, because the wheel diameter and number of revolutions are fixed. Therefore, under the given test parameters, the product VH for the material in the standard test is constant.

Standard wear test results can be used to assess the comparative energy dissipation (loss) values of different materials. Equation 2.4 is particularly true where Archard's equation is valid, such as in abrasive wear.

Binding Energy at the Surface or Surface Energy. A crystalline material is made up of unit cells containing the repeat unit of atoms and molecules. The atomic or molecular units are bound by cohesive energy. The binding energy at the surface is less than that at the bulk. The energy associated with the atoms bound in the surface is the surface energy. The applied force (F_n) should be equal or greater than the surface energy in order to dislodge material from the surface. For example, tungsten, with a high binding energy (8.66 eV), requires more energy than iron, with a lower binding energy, for removal of material from the surface by wear (Ref 2.17). In coating or a modified surface with high hardness, the surface energy is different than the bulk of solid material constituting the substrate.

Yield Strength. The yield strength or proof stress of a material is defined as the stress at which material begins to deform plastically, leading to dimensional changes in the solid. The yield stress is therefore the minimum stress (energy) required to cause dimensional change in the solid through plastic flow of material. The deformation process leads to an increase in the yield stress with increasing strain and becomes equal to the tensile strength when the material is fully hardened. The wear resistance of the surface increases with deformation and is at maximum at the work-hardened state.

Although hardness is used in Archard's equation for wear (Eq 2.1), the yield stress is a better choice to define material wear. The stress required for the onset of deformation and wear of materials is equal to the yield stress and roughly equals the hardness in Vicker's hardness number.

Wear Coefficient (*K*) of Different Materials and Wear Types. Standard test results show specific ranges of *K*-values for different types of wear (Table 2.2). The wear coefficient values vary over wide ranges. The wear coefficient for adhesive wear (K_{adh}) for identical metal pairs ranges from 10^{-2} to 10^{-7} (Ref 2.18). The wear coefficient for abrasive wear (K_{abr}) ranges similarly, from $10^{-0.5}$ to 10^{-5} (Ref 2.18). Erosion (K_{er}) ranges between $10^{-4.5}$ and $10^{-1.5}$ (Ref 2.19). By selecting appropriate tribomaterial, reduction of wear on the order of 10^3- to 10^5-fold can be achieved.

Wear coefficient data can provide valuable information on the wear process, including (Ref 2.18):

- *Wear mode:* By comparing the calculated *K*-value with field data or the experimentally obtained *K*-value, it is possible to identify the type of wear.
- *The proper material and lubrication system:* If the maximum allowable wear rate, life expectancy, and loading conditions are specified, one can recommend the appropriate material and lubrication system from the value of the wear coefficient.
- *Material response to wear:* The wear coefficient *K* establishes the proportionality and can be used as a measure of the material wear behavior (Ref 2.15). Both *K* and *H* reveal the material response and thus can be grouped in a single parameter, called the specific wear rate, $k = K/H = V/F_n \cdot d$, which can be used instead of the wear coefficient *K*.

Limitations of the Wear Equation. Archard's equation can be used to a limited extent to describe the abrasive and adhesive wear but not erosion, fretting, contact fatigue, or corrosive wear. Each type of wear has a different mechanism, cause, and effect. In the case of adhesive wear, the equation can be applied to bearings, gears, and other sliding systems but not to rolling systems (Ref 2.20).

Even with limitations, the formula is useful if the other influencing effects are recognized and if experimentally derived data are judiciously applied to compensate for limitations.

Table 2.2 Ranges of wear coefficients (*K*-values) for different types of wear

Wear type	*K*-value
Adhesive (K_{adh})	
Identical metals	10^{-2} to 10^{-7}(a)
Compatible metals	$10^{-2.5}$ to 10^{-7}(a)
Partly compatible metals	10^{-3} to 10^{-7}(a)
Nonmetals on metals or nonmetals	10^{-4} to $10^{-5.5}$(a)
Abrasive (K_{abr})	
Two-body abrasion	$10^{-0.5}$ to $10^{-2.5}$
Three-body abrasion	$10^{-2.5}$ to 10^{-5}(b)
Corrosive (K_{corr})	10^{-2} to $10^{-5.5}$
Fretting (K_{fret})	10^{-4} to 10^{-7}(a)
Erosion (K_{er})	$10^{-4.5}$ to $10^{-1.5}$

(a) Depends on the extent of lubrication. (b) Depends on low or high abrasive content. Source: Ref 2.18

Wear Tests

Standard wear tests are conducted to determine the amount of material removal during a specified test period under well-defined conditions. The ASTM International standard practices for wear tests are formulated by the respective subcommittees under ASTM Committee G-2. Some of the standards for adhesion, abrasion, and erosion tests are listed in Table 2.3. The results of the wear tests are reported as volume loss in mm^3. The wear coefficient K is calculated from the volume loss, applied load, sliding distance, and hardness of the material. The standard test data are normally used for ranking the materials in accordance to their wear-resistant properties for the specified type of wear.

The depth of the wear scar is considered a reliable method for assessing material loss. A surface profilometer can measure and record these values with ease. A more exact method using a profilometer and computer-control equipment was developed by George and Radcliffe (Ref 2.21). This process produces an isometric plot of the wear scar; the wear scar volumes are calculated by the computer automatically.

Wear simulation tests are carried out in a wear environment similar to that in actual working conditions for a particular application. Wear simulation test data are useful in controlling wear in the application for which the test is designed.

To produce accurate, reproducible, and meaningful results in wear tests, one must strictly follow the procedures spelled out in the specification. Some of the important features of wear tests include:

- Wear is expressed as volume loss. This is because there is no mass loss in deformation wear, although volume loss has occurred from the working surface. A 14 g loss from tungsten carbide (density of tungsten carbide is 14 g/cm^3) results in the same volume loss for 3 g of aluminum alloys (density of aluminum is 3 g/cm^3). Hence, mass loss in wear provides deceptive wear data.
- Any departure from the procedure stipulated in the standard must be reported along with the result. For example, ASTM G65, procedure A, stipulates 6000 wheel rotations. Any test result reported with fewer rotations should include the actual number of rotations with the data.

Table 2.3 Selected ASTM International standard practices for wear testing

Designation	Standard test method for:
G65	Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus
G105	Conducting Wet Sand/Rubber Wheel Abrasion Tests
G75	Determination of Slurry Abrasivity (Miller Number) and Slurry Abrasion Response of Materials (SAR Number)
G98	Galling Resistance of Materials
G99	Wear Testing with a Pin-on-Disk Apparatus
G73	Liquid Impingement Erosion Testing
G76	Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets
G102	Calculation of Corrosion Rates and Related Information from Electrochemical Measurements
G59	Conducting Potentiodynamic Polarization Resistance Measurements

Source: Ref 2.1