Koji KATO*
*Department of Mechanical Engineering, College of Engineering, Nihon University
1 Nakagawara, Tokusada, Tamuramachi, Koriyama, Fukushima 963-8642, Japan
E-mail: koji@mech.ce.nihon-u.ac.jp

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Abstract
In the past 250 years, natural resources have been consumed with very high speed and the earth is seriously
damaged and polluted. Tribology supported powerful and high speed machinery run by the energy from coal
and oil in the period with technologies of saving energy and materials. Many kinds of resources reserves
including those of energy and metals are being depleted within one hundred years. Revolitional technologies
of sustainability and zero-emission are being strongly required in the world industries to establish new
lifestyles of real health and sustainability for the eternal living of human beings and other lives in a symbiotic
way. Tribology is expected to develop its science and technology for the needs in industries and support a new
industrial revolution.

Keywords: Tribology, Technology, Industry, Energy, Materials, Resources, Depletion, Environment, Pollution,
Sustainability, Zero-emission, Health, Savings, Revolution

1. Introduction

Since the start of Industrial Revolution in the middle of 18th century in Great Britain, the power and speed of
machinery have been increased year by year till today. Present electric train running with the speed around 300km/hr
is one example to show the speed change in the past 250 years. As a result, the “mechanical and thermal severities of
contact” of machine elements in relative motion have been similarly increased to high levels in the period. The
introduction of very severe environments of high temperature, high pressure and corrosive media into practical systems
increased the “chemical severity of contact” at the same time.

“Lubricants and theories of contact, friction and lubrication” have been developed in the period to overcome the
severities and realize reliable and efficient transmission systems including bearings, gears and friction belts. “Wear
laws” have been studied intensively in the last 50 years and anti-wear materials and surface modification methods have
been developed for having higher reliability and longer life of machinery, and for higher productivity.

The big economic contribution of saving the costs of energy, materials and maintenance by reducing friction and
wear was confirmed and reported by the Jost Report (1966), which introduced a new word of “Tribology” to describe
the field of science and technology of this character. Its concept and importance have been well recognized since then in
various fields of industries.

All industries are now facing to the facts of “Depletion of Resources Reserves” of energy and metals in the coming
50 years and the “Critical Pollution” of air, water and soil. It is clearly required to develop technologies of
“Sustainability and Zero-emission” for the everlasting healthy living of all lives.

Tribology is expected to contribute to the technical challenges through its original way. This paper aims at
reviewing the essential parts of tribological achievements in the past 250 years and proposing its expected challenges
for the coming 50 years.

2. Representative machinery and tribo-elements in the past 250 Years

Representative machinery and tribo-elements are listed chronologically in Fig.1 where a large part of information
of names and years are from the book of “History of Tribology” by D. Dowson (1979). We may confirm in the figure that the steam engine could perform well by having the piston ring introduced by J. Watt and the improved metallic piston rings have been essential key elements for the petrol engine since its introduction in 1885 by G. Daimler and K. Bentz.

We may also confirm that the industrial generation of electricity at a power plant was made possible by the introduction of reliable large bearings, such as the tilting pad bearing by A. Kingsbury in 1898, and electric motors for machines and devices could be popularly used by having the reliable and less-expensive ball bearings developed in early 1900s.

The reliable performances of modern petrol engines, turbines, and jet engines have been made possible by having the developed transmission systems of bearings and gears. Lubricants for them have been mainly made from oil which has been the major source of energy for machinery since 1850.

For the modern industries and their products, bearings and gears lubricated by oil are not all tribo-elements but many others have been newly developed. They include seals of gases and liquids, brakes and tires, electric wires and strips, magnetic heads and tapes/discs, greaseless guides, oil-less dry metal cutting tools, metal forming tools, hip/knee joints and joints of robots in the space.

The introduction of a new word “Tribology” was timely to describe the science and technology for modern industries and the expressions of “Space & aero-, Vehicle-, Process-, Information- storage-, Maintenance-, Bio-, Nano-, Eco- and Geo-tribology” have been introduced in the last 50 years to characterize the role of tribology in each characteristic field of industry.

![Fig. 1 Representative machinery and tribo-elements introduced in the period of Industrial Revolution and Oil Age.](image-url)
3. Empirical laws and theories of friction, lubrication and wear

The empirical laws and theories of friction, lubrication and wear established in the period from 1470 to 2000 are listed chronologically in Fig. 2 together with the schematic diagrams to show observed characteristics of friction, lubrication and wear. A large part of information of names and years in the figure are from “History of Tribology” by D. Dowson (1979).

We may confirm in the figure that the mechanisms of the empirical friction laws observed by Leonardo da Vinci in 1470 were scientifically explained with the theory of adhesion at real contacts after about 500 years by F. Bowden and D. Tabor (1954, 1964) on the base of elastic contact theory of H. Hertz (1882). The contact mechanics was further developed and decried by K. L. Johnson (1985) in his book.

In contrast, the basic understanding of mechanisms of film lubrication and the development of its theory were relatively quickly made in the period from 1880 to 1970 starting with the pioneering works by B. Tower (1883) and O. Reynolds (1886), and a firm theoretical base for the design of lubricated bearing and rotors was constructed as shown by D. Dowson & G. R. Higginson (1966), A. Cameron (1966) and Y. Hori (2006) in their books.

The demand of minimizing wear in industry became crucial after 1920 as the severities of contact were extremely increased under the increased needs of poorly lubricated or unlubricated friction requiring higher reliability and longer life. Lubrication and wear were intensively studied as shown by J. M. Georges (2000) in his book.

Very fundamental wear laws were experimentally introduced by A. Palmgren (1945), J. Archard (1953) and M. Khruslov (1957) till 1960 for typical metallic materials and following research results were compiled in a handbook by M. B. Peterson and W. O. Winer (1980). Several wear modes were microscopically well observed with the SEM and wear maps were introduced by S. C. Lim & M. F. Ashby (1987), K. Hokkirigawa & K. Kato (1988) and K. Adachi et al. (1997). However, comprehensive wear theories are not yet well established for the design of contact materials and tribo-elements.

![Fig. 2 Empirical laws and theories of friction, lubrication and wear established in the past 550 years](image-url)
4. Examples of tribo-elements for modern machinery made in Japan in the past 50 Years

Fig. 3 chronologically shows 14 selections of modern machines and tribo-elements produced in Japan in the past 50 years. They are introduced from the 50th Anniversary Report of Japanese Society of Tribologists (2007).

The head/disk drive system in 1957 was designed with the theory of aero-dynamic lubrication and it has been developed in the following 50 years for the smaller size and larger capacity.

The electric high speed train called Shinkan-sen ran at the speed of 210 km/hr in 1964 and now runs at above 270 km/hr. The control of friction and wear at wheel/rail and electric wire/strip and the high reliability of rolling bearings are the key technologies for such a high speed rail way. A rotary engine was finally installed in a commercial car in 1967 by overcoming the problem of wear at the apexes of rotor.

DLC coatings first synthesized in 1970 were later introduced to the sliding valve in water tap and the guide in camera, and greases were totally removed from their sliding surfaces. An automatic transmission for a car became popular in 1973, where power was transmitted by friction between surfaces of metal and paper plates in oil. A turbo-charger of floating bush bearing was introduced to a car in 1979 for higher efficiency of combustion engine.

A very large tilting pad bearing for a $\Phi 20''$ rotary shaft was installed in a turbine generator in 1980. Ceramic rolling bearings were mass produced in 1987. Oil-less tower link bearings were used in 1985 in the world longest bridge over the inland sea between Japan main island and Shikoku island. Bearings for non-CFC compressor were developed in 1989.

Plastic thrust bearings of PTFE/GF/MoS2 were introduced in 1994 to a water turbine for power generation. Bearings and seals were made for a turbo-pump supplying liquid hydrogen and oxygen to a rocket engine in 1994. Lead free over lay was introduced to engine crank shaft bearings in 1998. A continuously variable transmission driven by the traction force was installed in a car in 1999.

The DN value reached $3 \times 10^6$ with hybrid ceramic bearings for a rocket engine in 2001 and $5 \times 10^6$ for a machine spindle in 2004. These successful achievements in industries are made possible by the fundamental knowledge of properties of friction and wear at the dry or lubricated contact interface shown in Fig. 2.

Fig. 3 Examples of machinery and tribo-elements made in Japan in the past 50 years (2007).
5. Tribology for savings and better functions

Table 1 introduces the industrial savings in UK (1965) by tribology in seven categories shown in the Jost Report (1966). The savings in categories of (a), (b) and (c) can be attained mainly by reducing wear and those in categories of (d) and (e) by reducing friction. Those savings are made by the improvements in “Safety, Reliability and Efficiency” of machinery through the reduction in wear and friction.

The economic contribution of this kind by tribology can be generally observed in any kind of machinery including automobiles, aircrafts, rail ways, power plants and production facilities. Separate surveys done in Canada, China, Germany, Japan, UK and USA concluded that investing in tribology could save up to 1.4% of GDP.

The other kind of contribution by tribology is to give useful functions to raise the value of machinery. The automatic transmission using friction plates and the continuously variable transmission using traction disks in Fig. 3 are examples of this kind. Those two types of transmissions are operated by friction at the contacts of friction plates or traction disks where high friction is required for the high efficiency of power transmission. High friction is the essential property at such contact interfaces for giving the function of power transmission to the system.

Grinding and polishing for finishing surfaces, friction welding for joining elements, rubbing for controlling liquid crystals and bolts/nuts for fixing elements make the similar kind of contribution of giving essential functions to elements and machinery by tribology, where low friction and low wear are not necessarily required.

Although they are not obvious in Fig. 3, their tribological contributions of giving necessary key functions to elements are very important in industry for realizing new or improved performances of machinery such as shown in the figure.

Table 1  Industrial savings by tribology in UK (1965)
from the Jost Report (1966)

| Category | Savings (million £) | % in Sum |
|----------|---------------------|----------|
| (a)      | 230                 | 45       |
| (b)      | 115                 | 22       |
| (c)      | 100                 | 19       |
| (d)      | 28                  | 5        |
| (e)      | 22                  | 4        |
| (f)      | 10                  | 2        |
| (g)      | 10                  | 2        |

6. Technical tasks in the age of depletion of resources reserves and the environmental pollution

Energy has been sufficiently supplied for the life of human beings from coal and oil and sufficient minerals by powerful mining in the past 250 years. Fig. 4 shows the available periods of resources reserves of energy and metals in the future with the speed of consumption in 2009 (Ministry of Environment Government of Japan, 2011 and BP Statistical Review, 2011).

It is very clear from the figure that new methods of obtaining energy from renewable sources and of using metals repeatedly without throwing away have to be developed within 50 years. Reproducible materials will become necessary for forming elements and machinery.

Fig. 5 shows the results of numerical simulations of the amount of natural resources, food per capita, industrial output per capita, pollution/(pollution in 1970) and population in the world by D.H.Medows, et al. (1972). The solid curve of “resources” in the figure partly corresponds to the diagram in Fig. 4 and describes the quick depletion of natural resources on the earth within 50 years. The solid line of “pollution” show extremely rapid increase in them caused by the rapid consumption of the natural resources and extensive emissions of pollutive by-products to air, water.
and soil.

As the result of such depletion in natural resources and coincided increase in pollution, the amount of industrial output and that of food in the world will suddenly drop before 2050 after experiencing their peaks, which will be similarly followed by the world population.

The facts shown in Fig. 4 and predictions shown in Fig. 5 tell us the strong and urgent needs of new technologies available to live without natural resources and pollutions in the environment. Reducing the amount of emissions of carbon dioxide reported by IPCC (2007) is a typical example requiring quick development of new technologies in the viewpoint of global warming.

Technical revolutions are necessary in industries for the use of renewable energy and recycled and/or reproduced materials without harmful emissions to the environment. Tribology is expected to take its role in such technical revolutions.

![Fig. 4 Resources reserves of energy and metals. (Ministry of the Environment, 2011) and (BP Statistical Review, 2011).](image1)

![Fig. 5 Simulations of the amount of natural resources, food per capita, industrial output per capita, population, and pollution/(pollution in 1970) in the world. (D. H. Meadows, et al. in 1972).](image2)

7. Revolutions in energy, materials & environment and design demands in 2000-2100

Human beings are now at the stage of changing their lifestyles from present ones of “Massproduction, Massconsumption and Throw-away” to new ones for the time of no natural resources of energy and minerals as shown in Figs. 4 and 5. They also have to be prepared for the negative impacts on their health and life by the accumulated pollution in air, water and soil. Chemically polluted foods and global warming are examples of the negative impacts.

Challenges to make revolutions in technologies of energy, materials and environment are clearly required for solving the problems and establishing new “Lifestyles of Health and Sustainability (LOHAS)” described by P.H. Ray and S.R. Anderson (2000) which would promise the ever lasting existence of human beings in symbiotic relationships with other living things.

Table 2 lists the essential keywords to describe those revolutions. “Energy revolution” will be made by changing sources of energy from oil, gas, uranium and coal to reproducible energy such as the sun, water, wind, ground heat and bio-mass. “Materials revolution” will be made by changing sources of materials from mines and wells to recyclable and/or reproducible ones. “Environment revolution” will be made by introducing new technologies for avoiding emissions of pollutive materials and/or replacing them with un-pollutive ones.

Technologies for the safe and reliable recovery of polluted air, water and soil will be required at the same time. New rules and laws to restrict emissions of pollutive ones will also be introduced for the successful revolution.

Industrial products in such an age of technical revolutions will have to satisfy the strong demand of “Sustainability” in addition to the traditional demands of high “Value” and low “Cost”, where sustainability includes no
pollution. Table 3 lists essential keywords related to the products in 2000-2100. In order to design products for the requirement, “Engineering” of renewable energy, recycling, reuse and reproduction of materials, zero-emission of pollutants and ecological balance will have to be developed. In determining the cost of a product, costs of recycling and/or reproducing materials will have to be considered.

Therefore, in the design of the value of a product, recyclability/reusability of materials and no-pollution will have to be seriously considered in addition to the traditional usefulness, performance, reliability, life and comfort.

LCA (Life Cycle Assessment) in 2000-2050 will mainly deal with the items in Table 3 for sustainability and cost, where tribology is expected to make contributions from the viewpoint of LCT (Life Cycle Tribology) for the better score of LCA of a product (Kato and Ito, 2004, 2005).

Table 2 Keywords to describe energy-, materials-, and environment revolutions in 2000-2100 AD

| Year | Energy Revolution | Materials Revolution | Environment Revolution |
|------|-------------------|----------------------|------------------------|
| 2000AD | Oil | Mining | Soil-Pollution |
| 2000AD | Gas | to | Water-Pollution |
| 2000AD | Uranium | to | Air-Pollution |
| 2000AD | Coal | to | Accumulated Pollution |
| 2100AD | Solar | Reuse | Zero-emissions and |
| 2100AD | Water | Recycle | total recovery from |
| 2100AD | Wind | (3R) | Accumulated Pollution |
| 2100AD | Ground | Reproduce | |
| 2100AD | Bio-mass | |

Table 3 Design demands of industrial products in 2000-2100 AD

| Value | Usefulness, Performance, Reliability, Life, Comfort, Reusability, Recyclability, No-pollution |
|-------|--------------------------------------------------------------------------------------------|
| Industrial Products | Sustainability : Renewable energy, Recycled materials, Reproduced materials, Reused materials, Ecological balance, No-pollution |
| Cost : Materials Manufacturing, Maintenance, Recycling, Reproduction |
| LCA : Life Cycle Assessment |
| LCT : Life Cycle Tribology |

In Fig. 6, the three white arrows schematically show the tribologically generated improvements of health & sustainability, cost-saving and value for one product. It would be important for traditional tribologists to consider possible ways of tribology to increase the improvements in the future by introducing new tribological concepts and approaches in the age of revolutions of energy, materials and environment.
8. Tribology for Sustainability in 2000-2050

Among the requirements in industry in the 21st century, sustainability will become an essential one which has not been seriously considered in the 20th century. The principal tribological approaches with the concept of sustainability are listed in Table 4, which are expected to be realized in 2000-2050. The keywords in the table are “light elements, coated surfaces, nano-design, control of wear particles & outgases, reproducible lubricants, on-purpose running-in, and on-demand lubrication.”

Figs. 7(a)-(g) introduce examples of experimental observations which seem to have high potentials of tribological applications for sustainability. Fig. 7(a) shows an example corresponding to (2) in Table 4, where the friction coefficient of about 0.001 is generated in dry nitrogen at the sliding contact interface between diamond-like carbon coatings containing hydrogen above 40% (Erdemir, et al., 2000). Fig. 7(b) shows an example corresponding to (3) in Table 4, where the introduction of micro-pits on the flat contact surface of SiC disk reduces the sliding friction coefficient by more than a half (Etsion, 2000). Fig. 7(c) shows the similar example of micro-texture effect on sliding friction in water, where the texture pattern of RSP on SiC disk gives the friction coefficient of about 0.0001 (Adachi, et al., 2006). Fig. 7(d) shows an example corresponding to (5) in Table 4, where the cutting force of metals is effectively reduced by having the spray of oil-coated water droplets much more than mineral base oil only (Yoshimura, et al., 2004). Fig. 7(e) shows a similar example, where nitrogen gas supplied in air to the sliding interface between CNx coating and Si3N4 ball reduces friction coefficient from about 0.70 to about 0.05 (Kato, et al., 2003). Fig. 7(f) also shows a similar example, where the friction coefficient around 0.02 is observed when nitrogen gas is supplied in air after the supply of oxygen gas for 50 cycles and the specific wear amount around 0.5x10^-7 mm^3/Nm is observed when nitrogen gas is supplied in air after the supply of dry air for 100 cycles (Adachi, et al., 2005). Fig. 7(g) shows an example corresponding to (7) in Table 4, where the friction coefficient between Si3N4 pin and SUS440C disk sliding in high vacuum is quickly reduced from about 0.3 to 0.05-0.10 by depositing indium vapour for 1-2 min on the wear track during sliding with the thickness of 2-4 nm. This amount of indium film keeps friction coefficient at around 0.05 for about 10^4 cycles after sufficient running-in (Kato, et al., 1990).

Many other new tribo-properties similar to those shown in Figs. 7 (a)-(g) will be found in the near future, and tribological technologies for sustainability will be developed.

Table 4  Tribological approaches for sustainability

| (1) Heavy tribo-elements of metals | Light tribo-elements of reproducible materials |
| (2) Bulk materials for contact surfaces | Coated surfaces for contacts |
| (3) “mm” to “μm” scale surface design | + nano-scale surface design |
| (4) No control of wear particles and tribo-outgases | On-purpose control of wear particles and tribo-outgases |
| (5) Mineral oil lubricants | Reproducible oils, water, gases, complex emulsions |
| (6) Resultant running-in surfaces | On-purpose running-in surfaces |
| (7) Over-supply of lubricant | Minimum supply of lubricant on demand |
Fig. 7  Examples of experimental observations useful for tribological applications of sustainability corresponding to the articles of (2), (3), (5) and (7) in Table 4. (Erdemir, et al., 2000), (Etzioni, 2000), (Adachi, et al., 2006), (Yoshimura, et al., 2004), (Kato, et al., 2003), (Adachi, et al., 2005) and (Kato, et al., 1990).
9. Concluding Remarks

Since the start of Industrial Revolution in 1750, the power and speed of machinery have been rapidly increased till now. The technology for controlling friction have been well established to support such industrial needs in 1750-2000 by developing tribo-elements, lubricants, lubrication methods and lubrication theory. Controlling wear became one more important subject in various industrial fields especially after 1950. Super alloys, ceramics and hard coatings have been developed as anti-wear materials. Wear maps were introduced to distinguish various wear modes. However, wear theories are not yet well developed to give design standards for wear control.

The well confirmed empirical laws of friction, wear and liquid film lubrication are summarized by the 18 schematic diagrams and key words to describe the observed phenomena in Fig. 8, where $F$:friction, $W$:load, $v$:sliding velocity, $A_a$:apparent contact area, $A_r$:real contact area, $\mu$:friction coefficient, $d$:film thickness, $\eta$:viscosity, $\omega$:angular velocity, $p$:contact pressure, $T$:temperature, $f$:normalized shear strength, $s$:shear strength of contact interface, $k$:bulk shear strength, $N_f$:fatigue limit cycle, $\Delta V$:wear volume, $L$:sliding distance, $D_p$:degree of penetration, $\tilde{P}$:normalized contact pressure, $\tilde{v}$:normalized sliding velocity, $S_m$:mechanical severity of contact, $S_t$:thermal severity of contact, $Y_f$:yield stress of film, $Y_b$:yield stress of bulk, $t$:coating film thickness, $a$:radius of Hertz contact area. The three images of EHLfilm, Tribolayer, and Micro-Plasma in the figure are by the courtesy of Prof.M.Kaneta, Dr.K.Ito and Dr.K.Nakayama respectively.

Fig.8 Schematic diagram of empirical laws of friction, wear and lubrication together with key words to describe the observed phenomena, and tribological challenges for the needs in the 21st century.
Mechanical, chemical and tribo-chemical approaches have been made to understand those empirical laws. The keywords of real contact area, adhesion, stiction, shake-down, liquid film, boundary layer, tribolayer, and fatigue-, abrasive-, adhesive-, & corrosive-wear have been introduced and well used to explain the observed phenomena. The Stribeck curve and wear map have become standard ways to describe observed properties of friction and wear.

In the 21st Century, tribologists are facing to a big change of industry which will be called as “The 3rd Industrial Revolution (J.Rifkin, 2011)” after “The 2nd and 1st Industrial Revolutions.” Fig.9 summarizes essential key words to describe them in relation to the amounts of natural resources and environmental pollution.

It is concluded in the figure that people in this century will give high value to the “Lifestyles of Health and Sustainability(LOHAS)” and leave the present lifestyles of massproduction, massconsumption and throw-away.

In the 3rd Industrial Revolution, reproducible energy and materials will form its base like iron, coal and oil formed the bases for the 1st and 2nd Industrial Revolutions. The industrial activity will be carried by the spirit of decentralization, collaboration and two-way among communities in the world, which is described as a horizontal type of development of industry. In the 1st and 2nd Industrial Revolutions, it was carried by the policy of centralization and top-down in general, which is described as a vertical type.

It must be necessary for present tribologists to understand such worldwide changes of industry from the historical viewpoint and find contributive ways of tribological technologies for the coming fifty years. Key words for such challenges are “Health and Sustainability.”

![Fig.9 The Industrial Revolutions and changes of lifestyles](image_url)
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