# Chapter 1
# Tribology—A Tool for Mechanical and Industrial Engineering

**Prasanta Sahoo and Suman Kalyan Das**

**Abstract** Human civilisation has employed the concepts of tribology from the very beginning if not in a formal way. It started with solving problems related to friction and lubrication in the activities of day-to-day life. Gradually with the interests of some bright minds, tribology began to take the form of a specific subject and humankind began to appreciate its potential of transforming their lives. Industrial revolutions definitely played a part in the development of tribology and benefits of same has been reciprocated back to the industries. The knowledge of tribology has now got an additional facet due to the present problems of energy conservation and climate change. Obviously, tribology has yet to offer lot more considering these aspects and the true potential of it can only be revealed by proper and wide application of it.

## 1.1 Introduction

The word 'Tribology' was first coined by the British commission guided by Peter Jost in his historic report in 1966. This marked the beginning of a unified approach to the studies and research related to the interaction between moving surfaces in contact. This led to other popular bodies adopt this terminology viz. the American Society of Mechanical Engineers (ASME) started a new division in 1983 by the name Tribology Division and the American Society of Lubrication Engineers renamed itself to the Society of Tribologists and Lubrication Engineers in 1985 [1]. Tribology is not a topic which is domain specific. Rather it is an interdisciplinary science encompassing the knowledge from physics, chemistry, material science, engineering, biology and so on to understand the phenomena occurring during contact of a pair of bodies in motion.

Tribology as a subject is very relevant for mechanical and industrial engineering. Friction which is one of major hindrances towards energy conservation nowadays, can be effectively managed with proper application of the knowledge of tribology. Wear which shortens the device service life and increases the down time of machineries can also be controlled to a great extent by knowing the proper tribological tools.

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Besides, other aspects like lubrication, surface engineering and corrosion which are almost a part and parcel of human society belong to the field of tribology. Hence, the significance of the tribological applications are evident more and more. But still, Tribology as a subject doesn't enjoy a very high visibility among the engineering and scientific community. Hence, proper awareness must be created about the subject and the present work is a small attempt in that direction.

## 1.2 Main Aspects of Tribology

Tribology is currently a matured subject of science and technology. As already mentioned it is related to interaction between moving surfaces in contact. The tribological interactions between two bodies give rise to various physics which can be explained by different theories and models (refer Fig. 1.1). Hence, tribology as a subject is highly multiphysical in nature. The types of phenomena that can take place in an interface and its local surroundings are as follows: mechanical (solid and fluid), thermal, electro-magnetic, metallurgical, quantum and others [2]. Among these phenomena, the significant ones are discussed in the following text.

### *1.2.1 Friction*

Friction is the resistance faced by a body (Fig. 1.2) when it slides tangentially on another body. Obviously, the friction force acts opposite to the direction of motion and exists even though the body is pushed but not in motion. The critical friction force which initiates the motion of the body is the static friction force which is normally

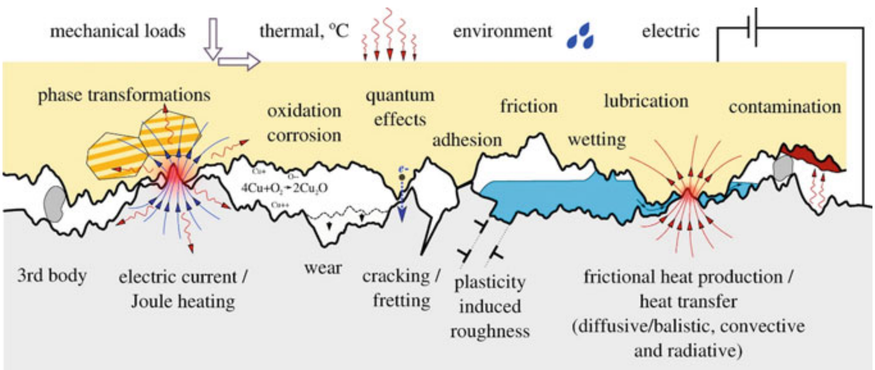


**Fig. 1.1** Multiphysical nature of tribology: two bodies make contact when exposed to various loads: mechanical, thermal, electric, and environmental [2]

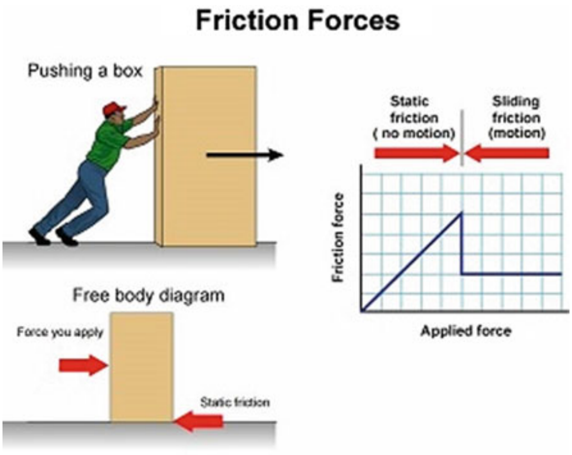


**Fig. 1.2** Friction (courtesy Vishakha.malhan under CC BY-SA 4.0 licence)

higher than the kinetic friction force i.e. the friction force experienced by the body once the motion starts. The significance of friction can mainly be categorised as [3]:

- Sufficiently higher friction for actions like walking, gripping, etc.
- Minimising friction in case of machinery.
- Maintaining a constant friction in case of precision devices, rolling industries, etc.

Experimental observation on friction over time has led to the following three empirical laws on sliding friction:

1. Friction force is proportional to the normal load acting between the two bodies in contact.
2. Friction force is independent of the apparent area of contact between the two bodies.
3. Friction force is independent of the sliding speed.

Apart from sliding friction, friction can also be like rolling friction which is experienced when a circular body rolls on a flat surface. Rolling friction is normally lower than sliding friction and is a popular configuration employed to lower friction in rotary parts of machines.

### *1.2.2 Wear*

Wear is the damage and gradual removal of material from one or both the contacting surfaces in relative motion. It is a system response and not a material property. In general wear is related to hardness of a material and higher hardness usually mean lower wear. The traditional means of measuring wear is by the weight loss suffered by the component. However, with advancement in instrumentation, wear is also represented in terms of depth. Wear is normally undesired as it leads to shortening of the service life of components. However, in some cases viz. machining, polishing, shearing, etc. wear is deliberately inflicted in a controlled manner.

Wear takes place either by a mechanical or a chemical process or by a combination of both. Wear is found to be accelerated in case of enhanced thermal conditions (high temperature conditions). Wear can be broadly classified as:

- Adhesive wear: occurs when two flat surfaces are in sliding contact and adhesion takes place at the interface particularly at the asperities.
- Abrasive wear: occurs when a softer surface is scratched by a harder surface.
- Corrosive wear: occurs when sliding between two surfaces takes place in corrosive environment.
- Fatigue wear: occurs during repeated sliding and rolling contacts.
- Erosive wear: occurs when material from a target surface is removed due to repeated impacts of solid particles.

### *1.2.3 Lubrication*

The idea of lubrication was initiated to reduce friction at first. But later it was found effective in limiting wear as well. Hence, much attention was given towards development of effective lubrication scheme. Lubrication is mainly achieved by including a medium separating the two surfaces intending to make contact. The medium is usually a liquid but, in some cases, it can be a suitable gas. Friction now depends on the resistance to shear deformation of the liquid which is nothing but the viscosity of the liquid. As the viscous forces are much lesser compared to the resisting force faced by the surface when making actual contact, friction is substantially reduced. Besides, as physical contact is avoided, wear is also limited to a great extent. Lubrication has seen tremendous evolution with time and based on applications there are now a variety of lubrication techniques which can be categorised as follows:

- Fluid lubrication
  - Liquid lubrication: Lubrication carried out by liquid
  - Gas lubrication: Lubrication carried out by gas
  - Boundary lubrication: Sliding surfaces are separated by a very thin molecular film of lubricant, so that the chemical and physical natures of the surfaces and the lubricant play significant role in the lubrication.
- Solid lubrication: Lubrication is carried out by inserting solid particles/ layer in between the two surfaces. The characteristics of these solid particles help in reducing friction and wear.

## 1.3 The Development of Tribology as a Science

### *1.3.1 Pre-history and Ancient Works (up to 1600 AD): Solving Simple Problems of Friction and Lubrication*

Ancient people obviously didn't have an organised knowledge in Tribology. They used common sense to solve problems related to friction, wear and lubrication. In fact, fire was believed to be discovered by the frictional heating between two stones. Gradually with time, human civilisations set up and there are definite proofs available regarding deliberate use of tribological techniques in order to overcome the issue of friction and wear. Early history of tribology is compiled and written in an organised way by Dowson [2].

One of the earliest evidences of the usage of tribological concepts can be found in the Egyptian civilisation. While constructing the pyramids, the rolling elements in the form of logs are known to have been used to transport heavy stones. This indicated that the people at that time were able to appreciate that rolling friction was lesser than sliding friction and required lesser energy. Besides, the popular painting about the transportation of a huge colossus aided by liquid lubrication also hints towards the basic knowledge of lubrication being known to them (refer Fig. 1.3). Water when used in appropriate amounts, made the sand stiff and reduced the sliding friction over sand by about 50% compared to when moving over dry sand [4]. The invention of wheel is considered to be an important milestone in the history of humankind. The same can also be considered to be a great proof about the tribological knowledge prevailing during that time. Sumerians and Mesopotamians are in fact believed to

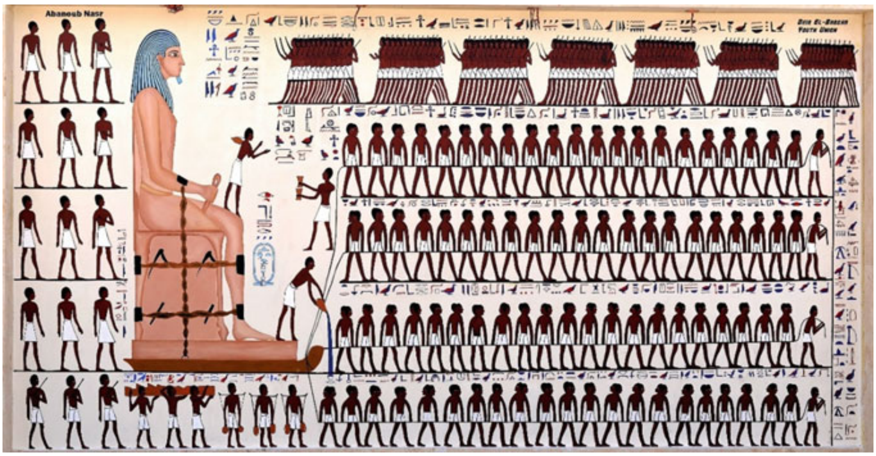

**Fig. 1.3** Transporting an Egyptian colossus from the tomb of Djehutihotep, El-Bersheh, (c.1880 B.C.) (courtesy Youssef Grace under CC BY-SA 4.0 licence) https://upload.wikimedia.org/wikipedia/commons/9/9b/Djhutyhotep_Deir_El-Barsha_Youth_Union.jpg

**Fig. 1.4** Ljubljana marshes wheel (courtesy - Petar Milošević under CC BY-SA 4.0 licence) https://upload.wikimedia.org/wikipedia/commons/8/85/Ljubljana_Marshes_Wheel_with_axle_%28oldest_wooden_wheel_yet_discovered%29.jpg

have used chariots for war. The oldest wheel and axle known as Ljubljana Marshes Wheel (Fig. 1.4) has been discovered in Ljubljana (Slovenia) and is dated to Copper Age (about 3000 BC). It is made of wood and indicates that wheels appeared almost simultaneously in Mesopotamia and Europe. Miniaturized wheel cart and toys have been unearthed from the sites of Harappan Civilisation. In fact, the people used bearings in wheel and axle system to concentrate wear in a single part.

Chariots have been found to be used by Ramesses II in various contemporary paintings. Ashurbanipal, the Assyrian king is believed to have used anti-wear protection for the wheel surface. In fact, the great literature of India, Mahabharata mentions the use of chariots in its text. The Greek and the Romans have contributed significantly in the field of tribology. Various mechanical systems viz. lathes, wheeled transport, pulleys, gears, mills, cranes, etc. were used by them [5].

Leonardo Da Vinci the great scientist has contributed significantly to the early development of tribology. He had great knowledge acquired from observations, logical reasoning and intuition which he employed to conduct scientific experiments in an organised way. From the various sketches obtained from his book, it is proved that he designed various devices based on tribological applications to solve problems of day-to-day life. Leonardo Da Vinci is the earliest person to conduct experiments on friction. In fact, he got the idea that friction is independent of contact area and also initiated the idea of lubrication in order to reduce friction. The sketches on ball bearings as proposed by Leonardo Da Vinci actually forms the basis of modern day ball bearings [6].

### *1.3.2 Classical Works (1600–1950): Transition of Tribology from Art Towards a Science*

The works undertaken during this period can be considered as classical works on tribology. They helped in establishing to some extent ‘Tribology’ as a science and technology of interacting surfaces. These works were undertaken mainly during the epochs of first and second industrial revolution and are characterized by improved designs of machine elements [7]. Significant portion of research undertaken during this period mainly concentrate on solving the problems related to friction and lubrication. However, there have been a few significant developments in understanding and modelling wear. Some of the important works during this period are discussed in the following sections:

- **Amontons (1699)**

Amonton carried out experiments on tribology particularly friction in a systematic manner. His works led to the establishment of two important laws of friction:

- Friction force is proportional to the normal load.
- Friction is independent of the apparent area of contact.
- **J.T. Desaguliers (1725)**

He carried out works related to cohesion of lead and suggested that adhesion might be relevant to friction.

- **Leonhard Euler (1748)**

He proposed a mathematical relationship for the coefficient of friction. He was the first to distinguish between the static and kinetic friction coefficient and stated that static friction is greater than kinetic friction. He believed in the rigid interlocking between asperities during sliding cotact.

- **Charles Coulomb (1785)**

Coulomb proposed the third law of friction which states that “Friction is independent of sliding speed.”

Coulomb in fact stated that friction happens due to the interlocking of asperities between the two contacting surfaces. His work verified the propositions made by Leonardo da Vinci and Amontons [7].

- **Gustav Adolf Hirn (1847–49)**

He was the first person to conduct experiments with lubricated contacts. He found that viscosity of the fluid played a significant role in lubricated sliding contact. Hirn further established a linear relationship for friction between a journal and bearing and the speed. As mineral oil was discovered around that period, Hirn used oil and found it to be an excellent lubricant.

- **Rudolf Hertz (1881)**

Hert basically investigated rolling friction [7]. He analytically determined the area between two solid surfaces in the elastic domain with geometries defined by quadratic surfaces [3].

- **N. P. Petrov (1883) and Tower (1883)**

Both Petrov and Tower conducted lubrication based studies in journal bearings. Petrov proposed that the friction in an adequately lubricated bearing is due to the viscous shearing of the fluid present in between the surface while Tower introduced the concept of hydrodynamic pressure in journal bearings.

- **Osborne Reynolds (1886)**

Reynolds gave the equation for the hydrodynamic pressure which is the basis of hydrodynamic lubrication theory [8]. This theory is the basis for the calculation of bearings. In fact, Reynolds stated that wear can be reduced to almost nil in case of sufficiently lubricated bearings.

- **Prantl (1928) and Tomlinson (1929)**

Both of them attempted independently to explain friction based on atomic theory [9]. Their theory laid the stepping stone towards the development of modern nano tribology. Prantl worked in the area of mechanics of plastic deformation. They proposed that during contact between two surfaces, the atoms slide over each other which affect their positions. They didn't consider wear in their model. Hence, according to them atoms would interact with each other within the intermolecular or interatomic range and won't move out of their position. During this interaction, the lattice goes into vibration and subsequently generate phonons as well as heat. This dissipated energy is reflected as friction.

- **Bowden and Tabor (1950)**

They gave the Junction Growth model to explain friction. The stated that friction force is contributed by two phenomena:

- Bearing of the normal load which results in mechanical interaction between the asperities (cohesive forces)
- Overcoming the attractive intermolecular forces (adhesive forces)

Now, during contact, the pressure at the tip of the contacting asperities makes the asperities deform plastically resulting in the real contact area to enlarge and get cold welded. The body needs to break these contacts in order to move forward which is reflected as the friction force [3].

### *1.3.3 Modern Works (1950–1990) Establishment of Tribology as a Science*

The modern period comprise the works carried out around the period of third industrial revolution. Based on the work done during the previous period, a clear understanding of friction and lubrication was obtained. However, due to lack of sophisticated experimental facilities, many of these theories could not be experimentally validated. Many of the works done validate these theories. Besides, the concept of wear was developed during this period.

- **Archard (1953)**

Archard was the first to deal with modelling of wear. He investigated wear problems which produced the classical equation for the volume of worn material [10].

- **Bailey and Courtney-Pratt (1955)**

They made pioneering work in the development of adhesion theory. They were able to measure the adhesion between two surfaces using two mica crossed cylinder method using Newton's interference fringes [11].

- **Dowson and GR Higginson (1959)**

They provided the numerical solution to the problems of elasto-hydrodynamic lubrication (EHL) which satisfied both elastic deformation of the contacting surfaces as well as hydrodynamic lubrication.

- **Greenwood and Williamson (1966)**

Surface roughness is a significant factor in the friction behaviour of a material as well as determining the transition between one lubrication regime to the other. Greenwood and Williamson proposed the first contact model considering roughness [12].

Surface roughness was recognized to play a major role in forming friction and transition from one lubrication regime to another [1]. Greenwood pioneered with first rough contact model in 1966 [12].

- **Jost Report (1966)**

This famous report formally gave rise to the term "Tribology" and highlighted the importance of studying various surface interaction phenomena particularly friction and wear so that machines with higher efficiency could be developed.

- **Tabor and Winterton (1968)**

They developed the surface force apparatus to get the first direct measurement of normal and retarded Vander Wall's forces between two mica sheets for separations less than 100 Å and 200 Å respectively [13].

- **Johnson, Kendall and Roberts (JKR model) (1971)**

They combined elasticity with adhesion to model the contact between two surfaces. Their theory is more suitable for contact between a soft surface with a harder one [3].

- **Suh (1973)**

Suh first put forward the delamination theory of wear [3].

- **Derjaguin, Muller and Toporon (DMT model) (1975)**

In addition to the normal load, they also considered the forces outside the actual contact area. This means the inter atomic forces outside the contact zone was considered along with the Hertzian contact model. This theory was more relevant for harder materials in contact [3].

- **D Tabor (1977)**

Tabor proposed the Tabor's coefficient, a parameter to determine the applicability of JKR or DMT model to define a particular contact between two bodies ending uncertainty of choosing between the two models [14].

- **Briscoe and Evans (1982)**

They performed the first experiments on the shear properties of mono layers of aliphatic carboxylic acids. They introduced the lubricant in between two smooth mica sheets [15]. Their work is significant w.r.t. nano-lubrication and nano-tribology.

Apart from the works already discussed, this period also saw application of numerical simulation towards solving or validation of various proposed models in tribology. Numerical scheme was applied to problems of elastohydrodynamics upto point contacts [16]. Besides, the concept of vanishingly low friction theory was proposed [17]. As the importance of energy conservation gradually cropped, developments were made in very low friction bearings [18] using air. Magnetic bearings also were developed. The concepts of surface engineering for customizing surface properties came into existence. As a result, various types of coatings were also developed.

Apart from these works, some reputed bodies were also formed during the second and third industrial revolution which carried out some of the outstanding works in tribology and even continuing to do so. Some of these bodies are [5]:

- Institution of Mechanical Engineers (IMechE, founded in London in 1847),
- American Society of Mechanical Engineers (ASME, founded in 1880)
- American Society for Testing Materials (ASTM, founded in 1898)
- American Gear Manufacturers Association (AGMA, founded in 1916)
- Society of Tribologists and Lubrication Engineers (STLE, founded in 1944 by ASLE, the American society of Lubrication engineers)
- Japanese Society of Tribologist (JAST, founded in1956).

## 1.4 Recent Progress in Tribological Research

Tribology has developed into a matured subject presently. From what started as solutions to simple problems of friction has evolved into understanding the same in atomistic and molecular level. Researches is this area today has grown both by scope and depth. There are now a wide range of academic journals available covering the multi-faceted aspects of tribology where articles on experimental as well as theoretical works are regularly published. These publications cover physics, chemistry, surface science, nanotechnology, materials science and engineering, biomedical engineering, as well as mechanical and manufacturing engineering [19].

### *1.4.1 Lubrication Related Advancements*

Lubrication being an important part of tribology, continuous effort has been ongoing in the development of more effective ways of lubrication. It has been reported that almost 1.0–1.4% of country's GDP may be saved by undergoing proper research and development in the field of lubrication [20]. This type of report has propelled the advancement in lubrication so that higher efficiency and durability of components could be achieved. In case of lubricants, the research is mainly in two avenues the first one being developing better base oils and second one to find effective additives. After all a commercial lubricant is mixture of a suitable base well with additives in it viz. antioxidants, detergents, dispersants, friction modifiers, antiwear and/or extreme-pressure additives, and viscosity modifiers [21]. However, there have been continual efforts to find new schemes and types of lubricants. Some of the contemporary works towards the development of lubricants and advanced lubrication schemes are presented in the following text:

#### 1.4.1.1 Additives

In case of liquid lubricants, about 70–90% is the base oil while the rest is additives [22]. Additives when included into the base oil imparts some specific properties into the oil. Sometimes new properties are brought into the oil by additives. While sometimes additives are employed to enhance a particular property already present in the oil. Some additives also help in avoiding/reducing undesirable changes in the oil during its service life. Based on properties induced, some of the additives are discussed as follows:

**Pour Point Depressant Additives**

This additive helps the oil retain its fluidity even at lower temperatures. At lower temperatures, there is a tendency of wax formation by the paraffin molecules present in oil. This affects the viscosity of the oil. Alkylaromatic polymers and polymethacrylates are commonly used additives in this class [23]. They help in reducing the pour point in modern oils by as low as 30 °C.

**Anti-Wear Additives**
As the name indicates these additives prevent wear and scuffing of the surfaces. They help particularly in boundary lubrication regime where there are chances of asperity to asperity contact between the bodies. As the additives are polar in nature, they get attached easily to the metallic surfaces. Subsequently during action, tribo and mechano-chemical reactions occur in this layer forming an anti-wear film on the component surface. This film protects the underlying metallic surface. Phosphorus compounds are normally used as anti-wear additives. However, the most popular additive used for a long time is Zinc dialkyldithiophosphate (ZDDP). However, due to its toxic nature, other additives viz. molybdenum-based additives act as replacements.

**Antioxidant Additives**
Oxidation prevention is required to enhance the life of lubricants particularly the components of the base oil. Oxidation is accelerated at higher temperatures. Moreover, the presence of wear debris and other contaminants also promote oxidation in the lubricant. Oxidation may lead to the formation of certain acids and sludge. The acids may corrode the surface while sludge tends to increase the viscosity of the oil. Some of the common antioxidant additives include Zinc dialkyl dithiophosphates, hindered phenols, sulphurized phenols, and aromatic amines. The formation of free radical reaction is hindered by these compounds as well as these compounds decomposes peroxides.

**Extreme Pressure Additives**
In some applications where severe sliding takes place, the lubricant may be subjected to higher temperature as well as higher loads. In these cases, due to elasto-hydrodynamic lubrication or even metal to metal contact, surface damage may occur. Here extreme pressure additives are added to the oil which help in reducing friction and wear. As they prevent surface damage, these additive are also sometimes referred to as anti-scuffing agents [22]. These additives have a chemical reaction with the surfaces in action and form a layer over the surfaces which is also insoluble to the oil. Moreover, the reaction is dependent on the localized temperatures generated by rubbing of the surfaces. Extreme pressure additives generally are sulphur and phosphorous compounds as well as chlorine and boron compounds. Ashless additives viz. dithiocarbamates, dithiophospates, thiolesters, phosphorothioates, thiadiazoles, aminephosphates, phosphites may be preferred in some applications where chlorine may cause corrosion. Apart from these, the lubricant also contains additives which promotes dispersion, prevents foaming and also prevents rust and corrosion.

#### 1.4.1.2 Nano Additives

As part of continuous development in liquid lubrication by the industry as well as the research community, the idea of using nano materials as additives in lubricating base oil came up. Nanomaterials due to their small atomic sizes are able to enter in the actual contact zones and create a protective layer which prevents the material from further wear and tear. Moreover, due to their higher surface activity, these materials can be adsorbed on the friction surface thereby resulting in a stable film. Due to these unique physical and chemical characteristics, there has been lot of interest in the use of these materials in the field of tribology. In fact, nano materials as additives have found to enhance the anti-wear characteristic of the oil together with reduction in friction and energy consumption. The nano-additives may be broadly classified into three types [25]:

| | |
|---|---|
| i. Nano-metal based additives | Includes pure metals, metal oxides, metal sulfides, metal hydroxides, and metal salts<br>e.g. Cu, Ag, Fe, Pd, Ni, CuO, ZnO, $Al_2O_3$, $TiO_2$, $ZrO_2$, $WS_2$, $MoS_2$, CuS, ZnS, CaCO3, LaF3 |
| ii. Nano-carbon based additives | Pure carbon: Nano Diamond, Fullerenes, Carbon Nanotubes, Graphene<br>Polymer: PTFE, PSS, PVP |
| iii. Nano-composite based additives | Cu-SiO2, Al2O3 -TiO2, Cu -MoS2, G -MoS2, α-Fe2O3 -GO, FeS2 -G, Ag -G, Cu -GO, Mn3O4 -G, La2O3 -PI, Alumina -MWCNT |

Some researchers have investigated the efficacy of using 2D nano additives in the lubricating oil. Nano materials having layered structure are frequently used as solid lubricants viz. graphite and $MoS_2$. In these materials, the shear strength between two layers is low due to weak Van der Waals force [26]. Hence, the layers can easily slide over each other thus providing the lubricating effect. In the same layer, atoms are bonded by covalent bonds rendering high modulus and strength to the structure [24]. Among the nano-additives, 2D nanomaterials have relatively higher specific area. This is an advantage as these materials can cover a larger area when adsorbed on the component surface. This way they can give higher protection to the surface and reduce the probability of metal to metal contact during sliding [27]. Figure 1.5 illustrates the application of 2D nano additives in liquid lubrication and its probable mechanisms. The performance comparison of a 2D nano additive (liquid like graphene) with pure water and graphene oxide (GO) is presented in Fig. 1.6. It is observed that liquid like graphene can achieve about 91% reduction in wear rate compared to water.

#### 1.4.1.3 Ionic Liquids

Lubrication scheme using Ionic Liquids (IL) was initially explored in 2001 [29]. ILs are salts which remain in molten state below 100 °C and particularly at ambient

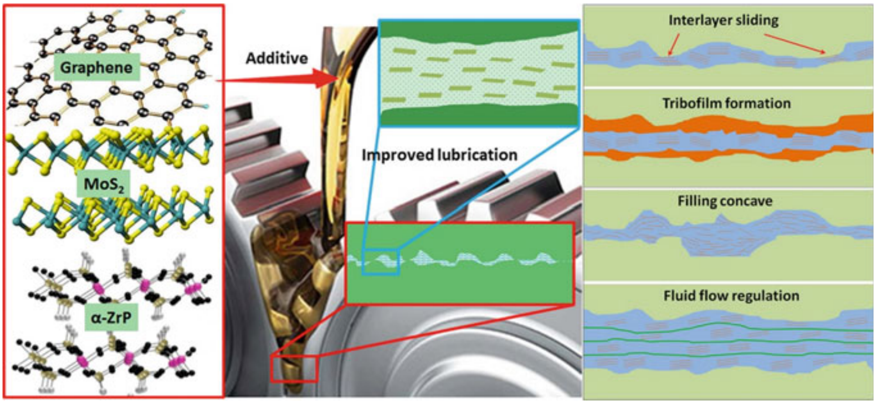


**Fig. 1.5** 2D nanosheets as lubricant additive and possible mechanisms for reducing friction and wear [24]

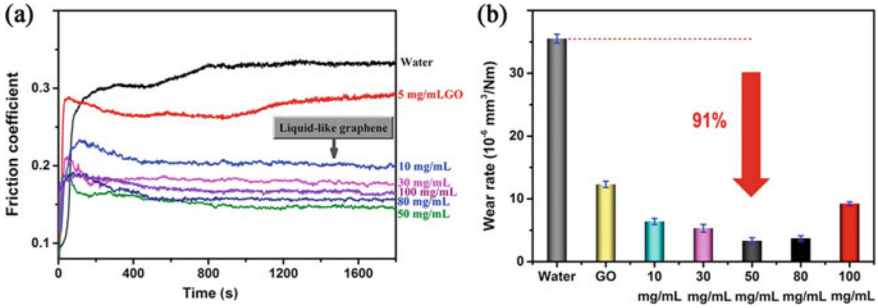


**Fig. 1.6** Performance comparison of liquid like graphene as additive with pure water and graphene oxide (GO) [28]

temperatures. They are called ionic as being a salt, the liquid consists of cations and anions. Hence, ILs have special properties viz. inherent polarity for strong surface adsorption, low volatility, higher thermal stability and lower flammability. Besides, unlike conventional liquid lubricants, ILs have low sensitivity (in terms of rheological behaviour) towards environmental variation. However, ILs alone are not economically viable to be used as lubricants. Again, ILs aren't readily soluble in commonly available nonpolar hydrocarbon lubricating oils. However, with advancement in research, some oil soluble ILs were reported around 2012 [30]. Those ILs also showed potential anti-wear capabilities. These resulted in new direction in research for lubricants where ILs were used as additives in oil. Figure 1.7 shows the structure of some of these additives.

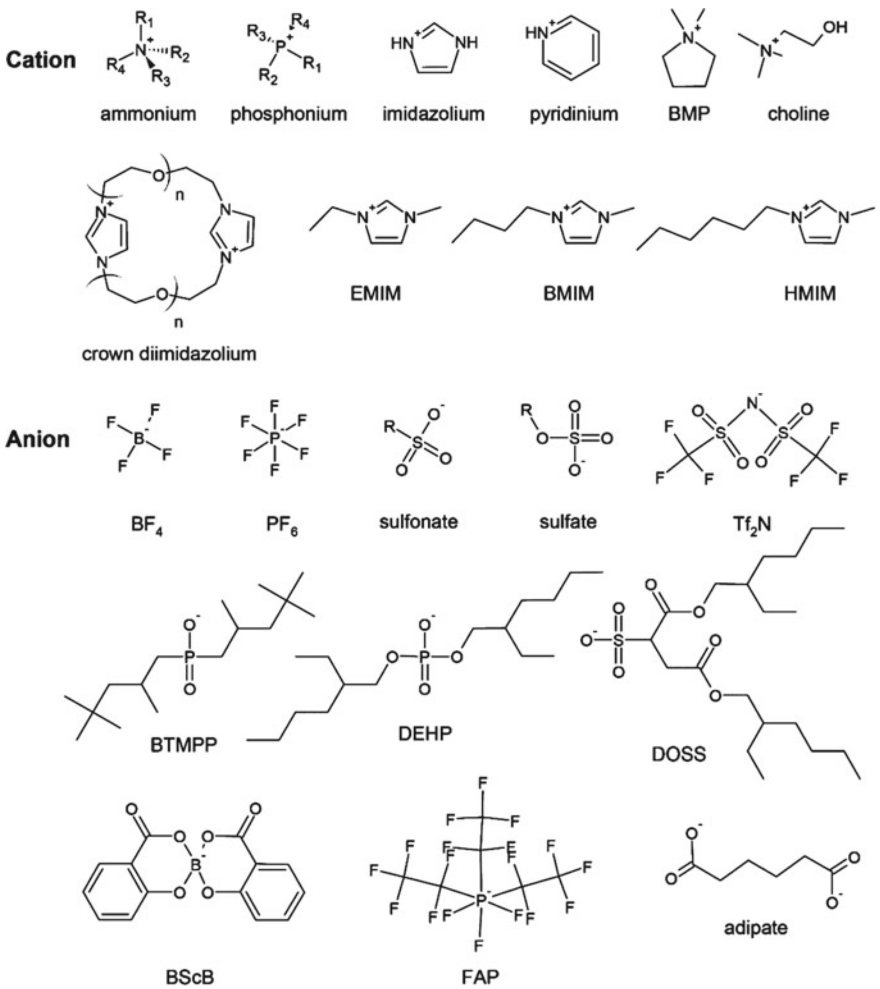


**Fig. 1.7** Structures and abbreviations of cations and anions of some ILs used as lubricant additives [21]

## *1.4.2 Super Lubricity*

Efforts have been continuously underway to reduce friction to save energy and increase the efficiency of various mechanical systems. The research on super lubricity is a step in this direction. Super lubricity is the condition in which friction is very low and is almost imperceptible. Actually, super lubricity occurs in a sliding regime in which physical and/or chemical interactions are so small that frictional resistance essentially is absent. This would yield tremendous energy savings as well as wear resistance. Further this would result in high efficiency machines with longer device service life. Super lubricity is one of the fastest developing fields in the recent years and if developed may be an important milestone in the history of tribology.

Several theories have been proposed to explain the phenomenon of super lubricity. Atomistic theory is one of them. Super lubricity can be categorised broadly into two types:

#### 1.4.2.1 Solid Super Lubricity

Diamond like carbon (DLC) film is already known for their solid lubricating capabilities. They have been further researched for lowering the friction significantly and for application in for super lubricity. In case of DLC, research have extended mainly in two avenues viz. DLC-based emerging lubricants and DLC-related lubricity mechanisms [19]. The research on DLC films have opened up scopes for developments of several lubricants.

Besides, various two-dimensional materials viz. graphene, carbon nanotubes, etc. seem to have potential for super-lubricity related research [19]. These materials have weak inter layer connection leading to very low shear resistance. Super lubricity can be achieved in many different systems and length scales. This has opened several new avenues for design of new mechanisms for this phenomenon.

#### 1.4.2.2 Liquid Super Lubricity

The mechanism for super-lubrication in case of liquids is dependent on mechanisms viz. hydration effect, chemical reaction layer, hydrodynamic effect, double electric layer interaction, etc. as well as a mixture of these mechanisms [19]. Commonly available liquids viz. water, acids, alcohols, acids, oils, etc. can act as base for the lubricant.

### *1.4.3 Surface Engineering*

Surface engineering is modifying the surface so that primarily a suitable friction and wear behaviour as needed in particular application can be obtained. However, surface engineering also involves changing the surface characteristics viz surface texture and imparting other properties viz. physical, chemical, electrical, electronic, magnetic, and corrosion-resistant properties depending on the application. Naturally, these types of requirements are faced by wide range of industries viz. automotive, aerospace, missile, power, electronic, biomedical, textile, petroleum, chemical, steel, cement, machine tools and construction industries. Surface engineering methods may be classified as follows [31]:

- Modification of surface with no compositional change

- Transformation hardening
- Surface melting
- Surface texturing

- Modification of surface involving compositional change
  - Solid solution and precipitation modification via diffusional processing
  - Formation of surface layers by thermochemical reactions with component material
  - Formation of surface layers by electrochemical reactions with the component material

- Coatings deposited on component surface
  - Coatings deposited from a solution of ions
  - Coatings deposited in the liquid state
  - Coatings deposited in the solid state

### *1.4.4 Advanced Surface Engineering Techniques*

Surface engineering has enormous potential to satisfy the requirements of various tribological applications. It can be highly customized for applications on case to case basis. It is found to be highly relevant in the domain of materials technology especially in aerospace, automotive, bio-medical and engineering applications recently. Although a lot of superior techniques have been developed viz. physical vapour deposition (PVD), chemical vapour deposition (CVD), diffusion processes, thermal spray, sol–gel, etc., still scope exists to establish relationship between the process parameters and the properties of the surface obtained. Besides, the increasing demands from industry require evolution of the surface engineering techniques so that components with high functional density could be achieved. This has given rise to multilayer and nano-structured coatings/nano-surfaces.

### *1.4.5 High Temperature Tribology*

Studying the tribological behaviour of materials under high temperature conditions are becoming important with respect to applications viz. automotive, aerospace, power generation, metal working, etc. Under high temperature conditions, especially when the ambient temperature is above the recrystallization temperature of the materials participating in tribological interaction, microstructural changes may be induced in the materials. This may lead to completely different tribological behaviour from the participating materials compared to normal room temperature conditions. Besides, a moderate high temperature condition may lead to grain softening and other phenomena which may further result in modified friction and wear behaviour of the

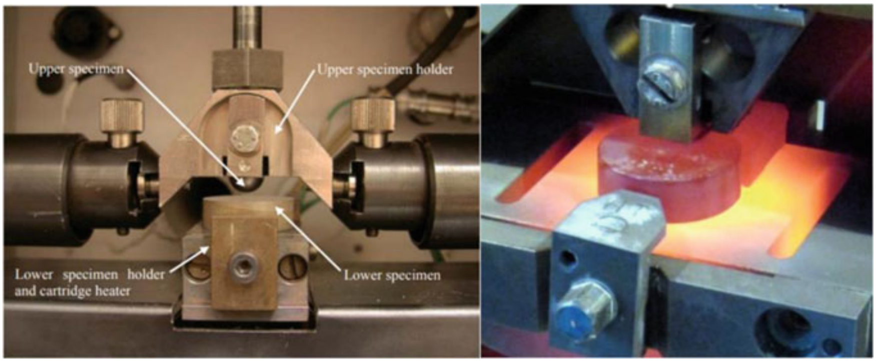


**Fig. 1.8** Test setup for high temperature reciprocating friction and wear tester [32] (under CC BY licence)

materials. Lubrication also poses a challenge in case of high temperature conditions. Based on temperatures generated, conventional liquid lubrication isn't possible in some applications which make the situation more challenging. However, the reliable functioning of the components is still expected and that too for an extended period of time.

The tribological phenomena are greatly affected by high temperature. High temperatures may generate frictional stresses which can lower the efficiency of a system. It is also to be kept in mind that high temperature situation can also be created by frictional heating without a sufficient heat dissipation rate. Elevated temperature can also aggravate the wear from materials as the material may soften in high temperature conditions. Various materials are researched which can withstand higher levels of temperatures. Moreover, suitable incorporations viz. refractory materials, etc. are made into surface coatings as part of surface engineering so that parts can display a stable friction and wear behaviour. Also, there is challenge to conduct friction and wear tests under high temperatures. Special tribo-testing apparatus have been developed to conduct these tests under laboratory scales (refer Fig. 1.8).

Many studies have been conducted in the area of high temperature tribology based on the needs of the industries. For automotive parts, lightweight materials are preferred from the point of fuel consumption. For this, materials viz. boron steel and ultra-high-strength aluminium alloys have been employed. The new generation coatings based on AlTiN are highly wear and abrasion resistant in high temperature conditions also.

#### 1.4.5.1 Lubrication for High Temperature Tribology

Selection of lubricant for high temperature application depends on many factors. Significant factors are viscosity, thermal stability and resistance towards oxidation. The lubricant ideally should have a very high viscosity but at the same time can be pumpable at normal temperature conditions. When exposed to elevated temperatures, the lubricant should be stable and should not leave residue on the hot surfaces. Moreover, it should not oxidize at higher temperature which implies hydrocarbon-based lubricant can't be the choice for high temperature applications. Even most of the popular base oils have thermal decomposition temperatures below 400 °C. A few lubricants viz. polyphenol ethers and silicates can be used at temperatures above 400 °C but they are solids at room temperature. The dropping point for most of the greases are also reported to be well below 400 °C. The dropping point is the temperature above which the grease loses its gel like consistency and behaves like a liquid. Hence, solid lubricants are the only choice for high temperature lubrication. Service temperature of some solid lubricants may reach up to 1000 °C.

In the modern day tribological systems, the component surfaces and even cores which intend to be in tribological interaction during the service conditions make use of solid-lubricating materials for high performance, efficiency, and durability. This makes them usable in a variety of tribological conditions over a wide range of temperature without suffering much wear and tear. The solid lubricating materials suitable for high temperature applications mainly comprise of a high temperature matrix material, high temperature solid lubricants as well as some supplementary components [33]. There are a variety of fabrication techniques to prepare the solid lubricant. Now, there are some challenges with respect to these techniques as the materials are sensitive to normal environmental conditions. Hence, research has advanced towards finding a novel material which can be used for making solid lubricants. In general, the lubrication mechanism of solid lubricants may be of the following types [33]: -

a. Materials in the form of layered structure with very low interlayer force (e.g. graphite, $MoS_2$)
b. Softer metals with multiple slip planes (e.g. Ag, Au)
c. Fluorides and oxides of metals with thermal softening (e.g. $CaF_2$, PbO, $AgMoO_4$).

Materials with layered structure are found to be effective at service temperatures below 400 °C. Above this temperature oxidation occurs in the materials. Fluoride, graphite and $WS_2$ can withstand temperatures up to 500 °C. Hexagonal Boron Nitride (hBN) can further withstand temperatures reaching up to 1000 °C. Fluorides and oxides of metals although quite effective in controlling friction and wear at elevated temperature, but fail to do so at room temperature or below. Figure 1.9 presents the working temperature for a variety of solid lubricants.

Ceramic materials have been included among solid lubricants for enhancing the thermal stability of the lubricants for temperatures touching 1000 °C. Ceramic materials have already proven themselves for controlling friction and wear and hence used in the new generation bearings. Besides, ceramics can effectively withstand corrosion as well as oxidation. The hardness of structural ceramic is found to be around 15–30GPa which is found to remain effective for higher levels of temperature as well [33]. Hence, this type of material can be suitable candidate for making solid lubricants for elevated temperature applications. However, ceramics are prone to micro fracture which is a major challenge as far as wear resistance and longevity

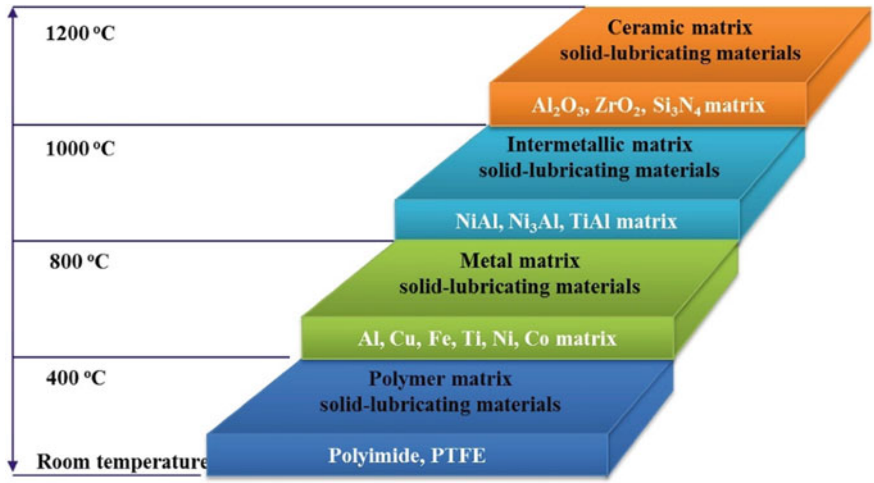


**Fig. 1.9** Working temperature range for solid lubricants [33]

of the component is considered. One of the ways to achieve these properties is to have a ceramic matrix with suitable incorporations in the form of composites. These matrices are mainly $ZrO_2$, $Al_2O_3$ and SiC based [33].

### *1.4.6 Computer Simulations of Tribology Phenomena*

Traditionally the tribological behaviour of a material is analysed through experimentation. The friction and wear behaviour can be obtained by using tribological testing devices which can have various contact configurations as desired. The most common of them is the pin-on-disc setup although various other setups like block on ring, ring on ring, ball on disc, etc. are available. Based on the configuration, the motion generated could be sliding or rolling. These setups allow the determination of mainly the coefficient of friction for a particular material pair as well as the wear rate. Some setups are also available with special arrangement and chambers so that the tests can be conducted at a specific temperature or environment. The wear mechanism can also be determined by observing the tested samples under high resolution microscopes. However, with the advancement in computer systems and increase in the computation power, simulation based techniques have gained popularity. Computer simulation allows to analyse a particular system without actually realizing it physically. Computer simulations have found broad applications in tribology viz. predicting wear of various systems, including cutting tools, bearings and artificial joints. Besides, various contact mechanics problems can be conveniently modelled and solved using these techniques. Nowadays, due to the introduction of nano tribology, tribological problems which were already multi physical in

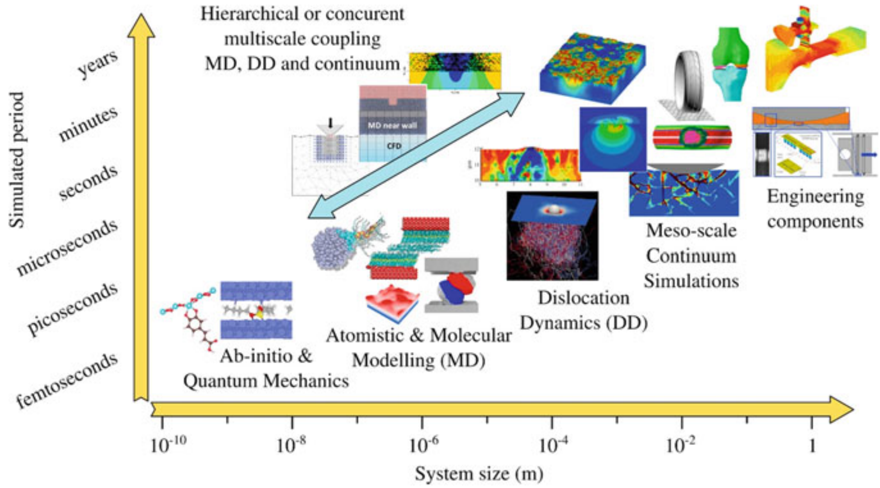


**Fig. 1.10** A time-versus length-scales map of models developed in tribology [2]

nature now vary a lot in scales. This micro and nano scale studies along with multi scale problems can quite efficiently be handled by these simulation tools which the researchers are increasingly embarking upon. Figure 1.10 illustrates various tribological models built across the scales. There are many simulation tools which can analyse the tribological scenarios quite effectively. The most commonly used ones are the finite elements and boundary elements method and molecular dynamics simulation.

#### 1.4.6.1 Finite Elements and Boundary Elements Method

The finite element method (FEM) and boundary element method (BEM) are popular tools used worldwide to solve various problems of mechanics and design. In FEM, an explicit relationship between stress and strain is considered with a finite strain formulation. Instead, in case of BEM, the relationship between force and pressure is considered with displacements in two orthogonal directions [41]. Several researchers have used this technique to investigate various problems in tribology a few of which are listed in Table 1.1.

#### 1.4.6.2 Molecular Dynamics Simulation

Molecular dynamics simulation (MD simulation) is a method of simulating and analysing the movements of atoms and molecules in a computer system. This is an atomistic approach towards understanding and explaining the behaviour of a system. In this method, the atoms and molecules are allowed to interact among themselves as they would in the real system but for a fixed period of time. This gives a view of

**Table 1.1** Application of FEM/BEM for studying tribological problems

| S. No. | Tribological issues | Simulation tool employed | Researcher/Research group |
|---|---|---|---|
| 1 | Effect of tool geometry on Ti6Al4V tool wear | FEM | Ducobu et al. [34] |
| 2 | Prediction of abrasive wear on steel against various types of copper ore | BEM | Perazzo et al. [35] |
| 3 | Effect of friction on relative wear on mining hopper | BEM | Rojas et al. [36] |
| 4 | Prediction of fretting fatigue and wear | FEM | Zhang et al. [37] |
| 5 | Simulation of scratching on polycarbonates polymer composite | FEM | Krop et al. [38] |
| 6 | Modelling fatigue life and wear on railway tracks | FEM | Lian et al. [39] |
| 7 | Prediction of the damage on fiber-reinforced polymers caused by adhesive wear | FEM | Din et al. [40] |

the dynamic evolution of the system. The path traced by the atoms and molecules are evaluated numerically using classical equations of motion. The interaction between the atoms and molecules are studied by considering interatomic potentials or molecular mechanics force fields. The MD methods have been successfully employed in fields of chemistry, materials science and biophysics.

In case of tribological research MD methods have well complemented the laboratory work. This is particularly due to the information about individual atomic interaction provided by this method and which is very much relevant to tribological interactions between two surfaces. Even though numerical methods have got a huge boost due to increase in the computational power, they sometimes face challenges due to time scale and system sizes. In a model system, there are typically thousands of atoms and system sizes in the range of tens of thousands of atoms. These restricts the typical size of the simulated tip as well as the sample below tens of nano meters in any direction [42].

Lately, MD simulation have become a popular tool for simulation of tribological system particularly through atomistic approach. Along with MD method, the first-principle calculations (computing atomic relationships via quantum mechanics) have also gained popularity in case of tribological simulations. These methods have been used to determine the molecular interactions at surface interfaces. These, simulation methods have been found to be particularly useful in explaining the actual dynamics occurring during friction and wear. However, these methods are also useful in studying the lubrication behaviour viz. boundary slippage occurring in lubricant rheology.

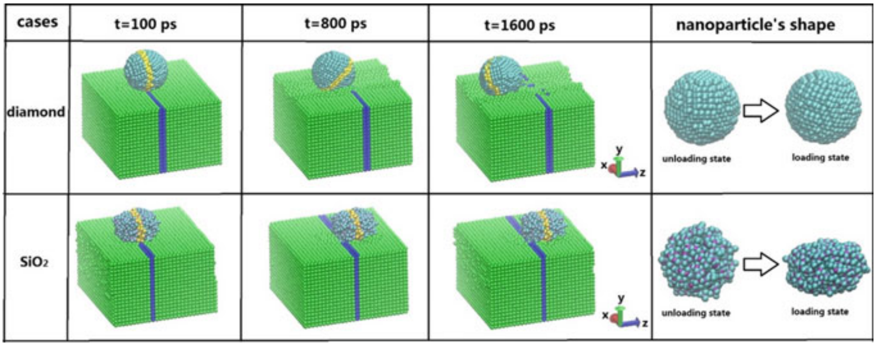


**Fig. 1.11** Rolling and deformation of diamond and $SiO_2$ nano particles. (upper block hidden for better visibility) [43]

Tribological behaviour of hard nano particles viz. diamond and silicon di-oxide ($SiO_2$) are simulated using MD technique (Fig. 1.11) [43]. The nano-particles are pressed between two iron blocks under a load of 1000 MPa. Apart from the naturally evident atoms, blue atoms are used to visualize deformation. Some part of the nano-particles is colour coded in yellow to mark the rotation of the nano particles. The nano-particles are found to separate the two blocks and undergo minimal plastic deformation. However, the diamond particle maintained its spherical shape owing to its higher hardness. On the other hand, $SiO_2$ particles are found to be deformed and crushed under the applied load. The yellow coded atoms reveal that even after application of load, diamond particle is still able to roll and acts as ball bearing between the two plates. But, the high deformation of $SiO_2$ particle prevents it from rolling.

In order to give rise to physically realistic models, researchers have presented multifactorial models where many factors can be analysed at the same time. However, these types of analysis require a large amount of computing resources which may increase the associated costs.

### *1.4.7 Biotribology*

As the research in tribology went intense, the various tribological interactions within the human body caught the attention of the researchers. This included, the phenomena occurring at the various joints of the human body, the teeth, the interaction due to the rubbing of the eyelids with the eyeball and so on. This encounter of tribology with the medical domain has given birth to the topic of bio-tribology.

Bio tribology is one of the growing fields in the area of tribology. As already mentioned it is devoted towards understanding the natural processes and how they work and function. How, diseases are developed and what medical solutions may

**Table 1.2** List of major topics in bio tribology research [19] (under CC BY 4.0 licence)

| Classification type | Major Investigations |
|---|---|
| Joint tribology | Natural synovial joints, articular cartilage, synovial fluid, mucin, and artificial replacement, etc |
| Skin tribology | Skin friction behavior, moisturiser and cosmetics, skin pathology, textile material, prosthesis, and tactile perception, etc |
| Oral tribology | Natural teeth, tongue, saliva, implant teeth, and dental restorative materials, etc |
| Tribology of other biological system | Tribology of other human bodies, medical device, animal tribology, and plant tribology, etc |

be suitable. Bio tribology encompasses a wide variety of areas. However, the main areas of research currently can be classified as presented in Table 1.2.

## *1.4.8 Biomimetics Tribology*

### 1.4.8.1 Hydrophobic Coatings—from Lotus Leaf

The surfaces which repel water are known as hydrophobic surfaces. In nature, lotus leaf is a very common example of having this type of surface. These surfaces normally provide the necessary roughness along with low surface energy which provides it the ability to repel water [44]. In case of superhydrophobic coatings, water can fully bounce upon hitting the surface. Tulip poplar leaf surface possess super hydrophobicity as can be seen in Fig. 1.12a. Figure 1.12b on the other hand shows a water droplet on a super hydrophobic coated surface. These coatings are made of composite

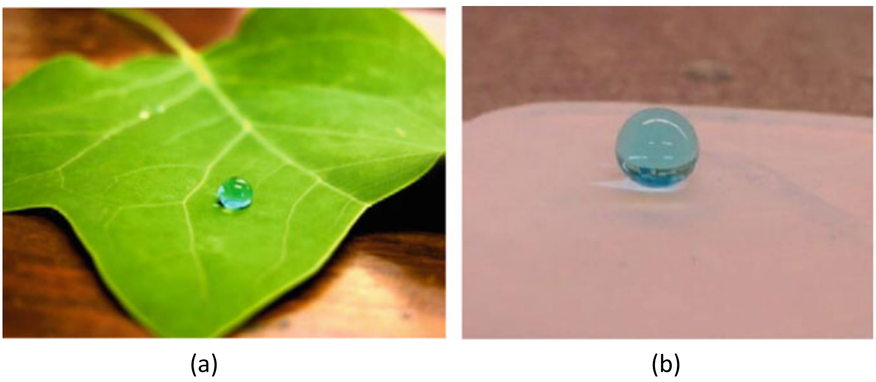


**Fig. 1.12** Water droplet on (**a**) Tulip poplar leaf and (**b**) super hydrophobic coated surface [44]

materials which can provide the optimal combination of surface roughness and surface energy. Some of the common bases for these coatings include:

- Manganese oxide polystyrene (MnO2/PS) nano-composite
- Zinc oxide polystyrene (ZnO/PS) nano-composite
- Carbon nano-tube structures
- Silica nano-coating

Silica based coatings are found to be amongst the cost-effective options available. The gel form of the coatings is easy to use as they can be applied to the surface of the object easily by dipping the object in the gel or through spraying.

There ae many utilities for these types of coatings. In the form of paints, they help in making various surfaces water repellent viz. umbrella, shoes, building materials, etc. In fact, various clothing can be made breathable and water repellent. This would eliminate the problem of sweating or getting the clothes drenched in rainy conditions. These coatings are further used in case of self-cleaning windows and lenses. This prevents moisture formation which is a problem in case of windshield of vehicles or mere glasses. Further, the glass can be cleaned by simply spraying water over them. The technique of self-cleaning is also useful for solar panels which many times are covered with dust over time. Hydrophobic coatings are also found useful in de-icing as the ice doesn't stick to the surface. This is particularly useful in cold countries where icing is a common problem. The cost involved in the de-icing procedure can be saved along with time and effort. As these coatings repel water, they prevent the formation of bacteria colony on surface and hence prevent bio-fouling as well. Besides, barnacles and mussels also can't get attached to these surfaces.

#### 1.4.8.2 Riblet Effect—from Shark Skin

The shark skin has microscopic scale like structures (Fig. 1.13) which lets water pass through them without forming vortices and hence reduces drag while swimming [46]. This technique has been effectively used in many air crafts sea vessels and even

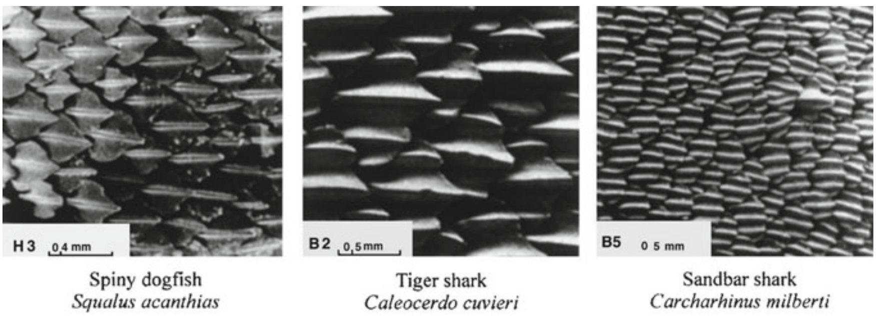


**Fig. 1.13** Scales on the skin of various shark species [45]

by the automotive industry. Airbus implemented riblet design for their aircraft wings and reported 6% lesser air drag which leads to significant savings in its fuel. Some swimsuit companies have taken inspiration from the riblet design for designing their range of swimsuits.

#### 1.4.8.3 Adhesive Surface—Gecko Effect

The remarkable adhesive strength displayed by the geckos in climbing walls has been the subject of interest for many researchers. Researchers have in fact investigated at the microstructural level and have found that the feet of geckos contain a complex hierarchical structure of lamellae, setae (microscale hairs), branches, and spatulae [48]. In each of the toes of the gecko, around 1.5 million setae are present. These setae further branch off into 100 – 1000 nanoscales spatulae (refer Fig. 1.14). Considering the surface area of each of the spatula, the cumulative area of contact becomes very high which leads to higher adhesion on various surfaces.

## 1.5 Spin-Offs from Research on Tribology

The research in tribology till date has already resulted in many spin-offs which has been very useful to the society at large. A few of them are listed in the following texts.

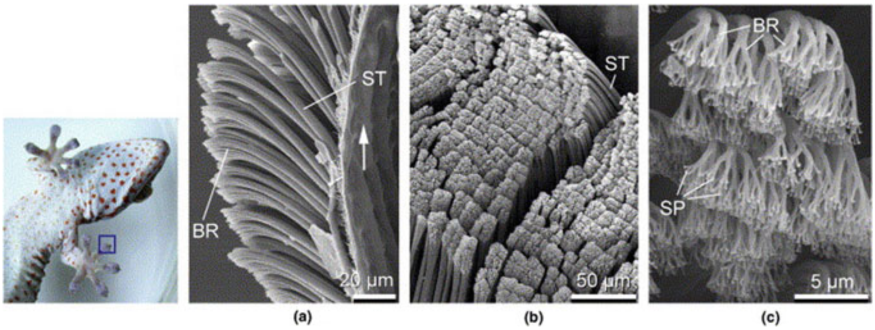


**Fig. 1.14** Gecko feet in detail (**a**) Rows of setae (ST) and (**b**) branches (BR) and (**c**) terminal spatulae (SP) from each seta [47]

**Fig. 1.15** Hard disk drive (courtesy Evan-Amos under CC BY-SA 4.0 licence) https://upload.wikimedia.org/wikipedia/commons/f/f8/Laptop-hard-drive-exposed.jpg

### *1.5.1 Hard Disk Drive Technology*

The advancement of computers has revolutionized the human civilization in the last few decades. With this advancement, the requirement of storing up of digital data came up. Research and knowledge in tribology proved to be very significant towards development of this technology. In a typical hard drive there are many discs which are mounted on the same spindle (Refer Fig. 1.15). A slider mounted on an actuator arm slides on the discs when the drive is in operation. The slider is a magnetic head and its contact with the disc results in reading and writing of data. Failure at the contact interface may result in erasure of the date. Moreover, generation of wear particles at the slider and disc interface may enter into some critical part leading to catastrophic failure of the whole system. Research in tribology has led to the development of protective carbon overcoats and boundary lubrication which maintain at least a monolayer of lubricants on the disc surface. Moreover, the topology of the disc can also now be precisely controlled. All these resulted in holding the recording head at a minimal gap from the disc surface thus reducing wear and tear considerably [49]. This has led to the prolonged life of the storage media as well as their increased reliability.

### *1.5.2 Ceramic Bearings*

Bearing technology is highly dependent on the knowledge in tribology. In fact, due to the progress in tribology, bearing technology has improved and given rise to next

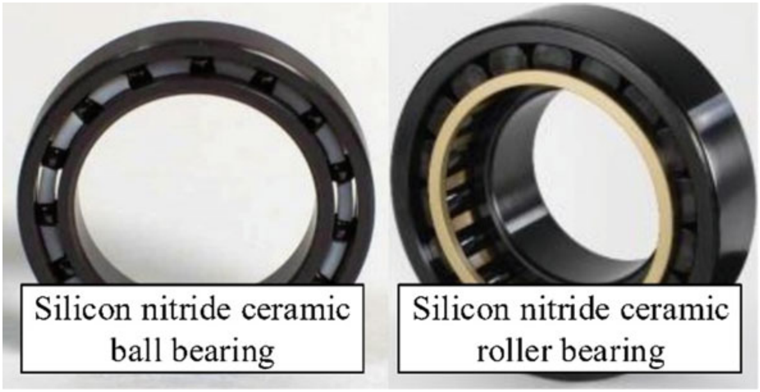


**Fig. 1.16** Ceramic bearing [50] (CC BY 3.0 licence)

generation of bearings. Ceramic bearing (refer Fig. 1.16) is one of them and they have the following advantages:

**Ability to Handle High Speed**
Compared to metallic bearings, ceramic bearings are advantageous as they can handle higher speed efficiently. This is because ceramic bearings present lower rolling resistance due to smoothness. This smoothness is due to the precision manufacturing which is possible in case of ceramic parts. They have higher dimensional accuracy over metallic, particularly steel bearings. This aids in distributing the service loads uniformly over all the rolling elements of the system. Moreover, ceramic material possesses lower coefficient of friction (about 20–30 times lower) than steel ball bearings under standard conditions of lubrication.

**Lighter Than Steel Bearings**
As a material, ceramic is much lighter compared to steel. Typically, they weigh about 40% lesser compared to steel counterparts. This lighter weight translates to lower centrifugal forces on the outer race when the bearing is in operation. Due to these lower forces, ceramic bearings are able to 20–40% faster than the conventional steel bearings. Or in other words, they consume relatively lower energy to maintain the same speed.

**Higher Stiffness Than Steel Bearings**
Ceramic bearings are also found to be stiffer compared to steel bearings and hence are more durable. Their service life is in fact roughly about 5–20 times longer than similar steel bearings. Smooth surface of ceramics reduces the risk of bearing seizure in case of limited lubrication. Moreover, ceramics bearings are known to be inert to most of the chemicals and hence can operate in harsh environment. Electrical insulation of ceramics also makes these bearings resistant against electrical erosion and pitting.

The development of ceramic bearings has improved various mechanical systems operating at high speed and at extremely high precision viz. ultracentrifuges, machine tool spindles, turbomolecular pumps, etc. NASA is reported to have increased the longevity of fuel feed pumps for their space missions by replacing them with ceramic bearings [49].

### 1.5.3 Durable Implants

The knowledge of tribology isn't limited to machinery and mechanical equipment only. The knowledge of tribology has been successfully implemented in case of biomedical applications. This has led to the development of high quality and durable implants. According to www.nature.com, "Biomedical materials are biomaterials that are manufactured or processed to be suitable for use as medical devices (or components thereof) and that are usually intended to be in long-term contact with biological materials." Thus, along with bio-compatibility the implants particularly those used in joints should have high resistance to wear and tear. This would enable higher life of the implant along with safety to the patient receiving it.

Knowledge of tribology enabled the selection of proper materials for biomedical implants. The suitable materials for joint replacement include Ultra High Molecular Weight Polyethylene (UHMWPE), Ceramics, Titanium and its alloys, etc. (Fig. 1.17). Ceramic on ceramic has been found to be very suitable in case of hip arthroplasty [51]. Ceramic has the perfect combination of hardness and durability and is highly resistant to wear. Besides, it doesn't have toxic effects on the body. Ceramics on plastics (UHMWPE) has also been recognised as good combination of materials for

**Fig. 1.17** Implants for hip arthroplasty (courtesy Science Museum Group, UK under CC BY-SA 4.0 licence) (https://upload.wikimedia.org/wikipedia/commons/4/47/Hip_joint_replacement%2C_United_States%2C_1998_Wellcome_L0060175.jpg)

arthroplasty. This combination has a potential wear at a rate of about 0.05 mm each year, which is 50% lesser than metal on polyethylene [51].

### *1.5.4 Development in Micro-electromechanical Systems (MEMS)*

Miniaturization and multifunctionality are the two keywords of modern-day engineering applications. Development and application of MEMS have seriously contributed towards these objectives. However, proper application of MEMS requires the understanding of friction and wear behaviour of surfaces at nano/micro levels. In fact, the extensive application of MEMS is often limited by poor tribological performance and adhesion issues. This is due to the high surface-to-volume ratio in MEMS and is typically a problem in case of actuator-based MEMS applications where inconsistent or high friction restrict the smooth movement of the components. Moreover, surface forces viz. meniscus force, surface tension, viscous drag and adhesive forces are quite significant comparing the size scale of the devices and components. These forces can have a large influence on the integrity of the devices thereby decreasing its performance and durability. Besides, the conventional lubrication techniques can't be used in these types of systems. An additional challenge is, silicon, which is a popular material in this type of applications and has poor tribological properties.

Based on these challenges, research has been pursued. It was clear that surface forces need to be minimized in order to have improved performance and life span of MEMS devices. Hence, investigation on modification of surface either by change in topography or chemical processing is carried out. Topography modification include the change in the surface roughness by texturing or similar so that friction behaviour could be altered. Chemical modification of the surfaces through coatings is also seen to yield promising results. Some of the suitable thin film coatings found suitable in case of MEMS include ionic liquids (IL), diamond-like carbon coatings (DLC) and self-assembled monolayers (SAM). Hence, tribology has contributed significantly towards the development of MEMS based devices.

## 1.6 New Paradigms in Tribology and Its Future

### *1.6.1 Trends in Lubrication*

#### 1.6.1.1 Liquid Lubrication

At present liquid lubrication are developed and improved keeping in mind the internal combustion engines (ICE) and drive trains. However, as environment friendly Electric Vehicles (EV) are gradually coming into the focus, the lubrication technology also needs a paradigm shift. This type of vehicles is driven by electric motors and due to the higher power density of the smaller gear boxes, there are heating issues. Hence, the lubricant should be able to efficiently cool the engine. Besides, right now the design variation of these engines is considerable and hence targeted use of lubricants based on a particular engine is required. The lubricant required in EVs have greater technical requirements compared to that of ICEs. Apart from acting as coolants, the lubricants should also possess good anti-wear capabilities, lowering friction, having electrical combability and insulation. EVs require lubricants in vital electrical components such as coolants for the car battery, gear oils for differentials, chassis, gear reducer, and wheels, brake fluids, and grease for other components of the EV. Electrical combability of the lubricant in the rolling element bearing of EVs help in mitigating the problem of electro-corrosion resulting from high frequency and high energy discharges. Ionic liquids have shown potential in preventing this type of charge accumulation [23].

#### 1.6.1.2 Solid Lubricants

Although great strides have been taken for the development of lubrication schemes for high temperature tribology, there are challenges faced by the industry in regards to their fabrication and implementation. The fundamentals of tribological mechanisms occurring at high temperature is yet to be understood fully. The basics are still majorly based on the understanding of solid lubrication theory. There are possibilities of further reduction in friction and wear and future materials should be directed towards this direction. In general, a friction coefficient < 0.2 and wear rate <10–6 $mm^3/Nm$ as well as the ability to sustain a wide range of temperature can be criterion for the future solid lubricants [33].

At present solid lubrication is developed keeping in mind the objective of reducing friction and wear. But as equipment become integrated and complex, need for multifunctional and smart lubricating material are gradually felt. Some examples of multifunctional requirements include structural/lubricating integrated material, anti-radiation lubricating material, conductive or insulation lubricating material, etc. Similarly, smarter capabilities are w.r.t. the abilities viz. self-diagnosis, self-repair, and self-adjust. A general trend for the development of high temperature solid lubricants is illustrated in Fig. 1.18.

### *1.6.2 Nano Tribology*

Nano tribology deals with atomic and molecular interactions often at nano scale which occur when frictional contact between two bodies occur or during lubrication. Initially, tribological studies were directed mainly towards understanding the macroscopic interaction between surfaces. However, with the introduction of advanced systems, viz. hard drives, MEMS, bio devices, etc., understanding the tribological

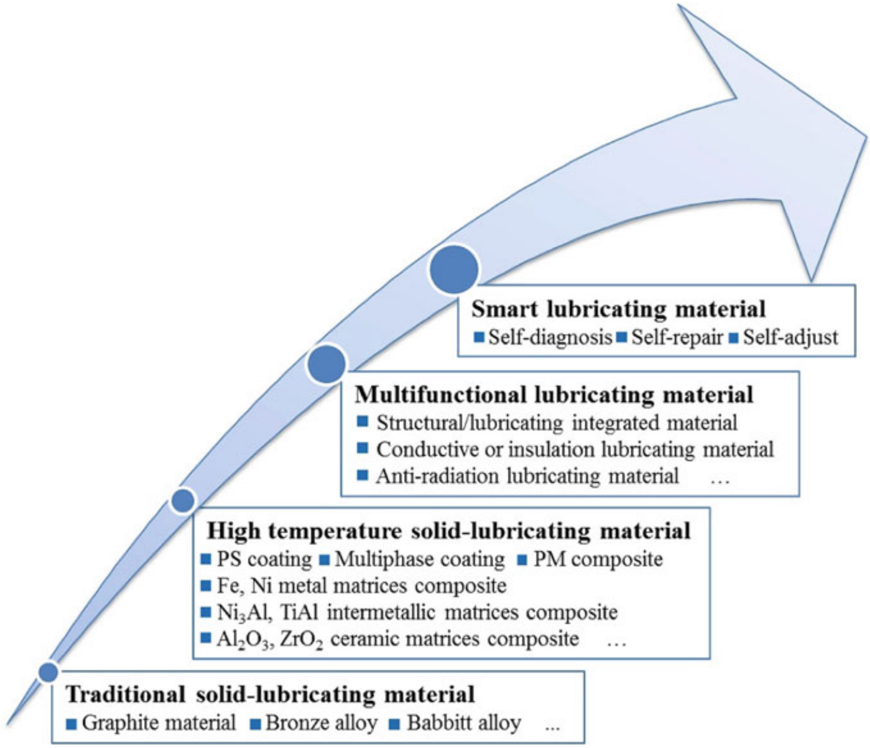


**Fig. 1.18** Future trends of solid lubricant for high temperature applications [33]

interaction at atomic level became a necessity. Hence, devices viz. Atomic Force Microscope (AFM) and other surface analysis methods are adopted for tribological investigations at molecular levels. Again, increase in the computational power led to the development of various simulation techniques which were able to model and simulate the interactions at nano/micro scales. With the development of nano materials viz. graphene, DLC, graphite etc. and their potential to revolutionize surface engineering as well as lubrication methods, nano tribology has become even more important today. Nano tribology can also help in the development of advanced drug delivery systems, chemical and bio detectors, molecular sieves, systems on chip, etc.

### *1.6.3 Emphasis on Green Tribology and Associated Research*

The environmental concern is growing serious day by day and has touched almost every aspect of our life. Environmentally sustainable engineering is the need of the hour for limiting loss of energy and associated carbon dioxide emission. In fact, the subject tribology has more to offer from environmental perspective than it has delivered till date. It has been reported that about 200,000 million litres of fuel (gasoline and diesel) is exhausted in overcoming frictional resistance in passenger cars alone [52]. Now, one can imagine how much energy and fuel can be saved by following proper tribological practice throughout the entire human civilization. Now, these types of reports started coming in towards the end of the last century. All these led to the formal introduction of the topic "Green Tribology" in the World Tribology Congress in Kyoto, Japan in 2009.

The basic principles of green tribology revolve around reduction of energy consumption, reducing pollution and emissions, usage of natural and biodegradable materials, sustainable lubrication, lower maintenance, etc. However, the focus areas of green tribology currently include.

- Application of biomimetics and self-lubricating materials/surfaces
- Eco-friendly lubrication and materials
- Renewable and/or sustainable sources of energy.

Some advancements are already made in each of the areas but more and more emphasis should be given in those and related areas keeping in mind the environment and climate change aspect which has really entered into a critical phase today. Getting influenced from the nature in providing solution to complex problems has already led to the development of surfaces with hydrophobic properties, strong adhesion, self-lubricating properties, etc. However, nature has still to offer many things and more diligent effort is required in this direction. Moreover, the already developed biomimetic technologies too require more fine tuning and cost-effective application so that they can be more widely accepted. Similarly, formulating lubricants with natural and bio-degradable ingredients is yet to receive the necessary impetus so that it may become a significant part of the society in general. In the future, the formation of lubricant may be customized for each tribological system so that they can run efficiently and for a longer duration of time. More stringent regulations are expected for the industrial lubricants so that ecological sustainability is guaranteed. Hence, new lubricants are expected to contribute to 'Green Tribology'.

Minimizing friction and wear are important from energy conservation perspective. Now, the various tribological systems associated with production of renewable energies viz. wind energy, marine energy, solar energy, geothermal energy, etc. require to be very efficient as well as eco-friendly so that maximum harnessing and utilisation of the energy is possible. The role of design and durability of many large-scale renewable energy systems is vital from sustainability aspect [53]. The efficient performance of the associated tribological parts are important as these systems are sensitive to operation and maintenance costs. Moreover, hydrogen which is normally used as secondary energy carrier and considered to be clean source of energy is anticipated to play a significant role in the future energy scenario. Hence, understanding the effect of hydrogen environment on the tribological behaviour of components viz. bearings and seals are an important aspect of research [54] which is projected to gain momentum in the future.

## 1.7 Tribology for Industry 4.0

Although tribology seems to be more of research topic but it is interesting to note that tribology and industry almost go hand in hand. Industry is very much concerned with the problems of friction and lubrication which are some of the basic attributes of tribology. The advancement in tribology has impacted the industry from the start of industrial revolutions till date. Moreover, industry time to time has presented some issues based on which innovation has taken place in the field of tribology. The significance of tribology in connection with industry is very much evident from various literatures and is almost always stressed in various key note lectures at conferences viz. World Tribology Congress [7].

Presently, the fourth industrial revolution 'Industry 4.0' is in progress which is basically about automation and internet of things (IoT) [7]. This implies that the device and machinery involved should be smart, efficient as well as can be controlled remotely. Based on these aspects, the following key areas may be the ones where tribology can contribute significantly.

### *1.7.1 Smart Tribology for Industrial Processes and Manufacturing*

Today's industry is smart and able to take a lot of decision on its own without the intervention of the humans. This capability comes from a wide variety of sensors and processors installed in the system. Now, tribology as a field is already reported to be quite compatible with electronics and ICT (information communication technologies). Hence, systems can be built where sensors may be able to tell the condition of the lubricant and the machinery. Data of the vibration of the machine or a temperature rise may indicate whether there is lack of lubrication. If there is a lack of lubrication, some automatic valve may open supplying the necessary amount of lubricant. Moreover, the quality check of the lubricant may also be carried out by another sensor to see if it needs to be totally replaced. Now, the machine should be connected to the internet so that the recorded data may be sent to the control unit for decision and subsequent action. The use of active controlled bearings in actuated tilting pad journal bearing is already reported in the literature [55]. Implementation of active lubrication helps in reducing the vibration of machine and improve the overall dynamic performance of the machine [7]. For this purpose, magneto-rheological and electro-rheological fluids can be used as lubricants [56]. However, considerable testing of these "field responsive fluids" needs to be done before final implementation as lubricants in a particular system. Hence, the implementation of the said strategies can definitely yield a production system which is smart and efficient.

### 1.7.2 Monitoring Maintenance and Diagnostics

The maintenance and monitoring of machineries are a vital part as these eliminate the machine breakdown costs as well as enhance the life of the machine. Bearings which come under the purview of tribology is an integral part of most of the machines. Now, bearings are the component which may indicate prediction of the service life as well as can be used for diagnostic analysis [7]. In fact, rolling bearings integrated with sensors have already been developed which is able to measure torque, forces, vibrations, etc. [7]. Moreover, the continuous monitoring of the lubricant may also reveal information about any undesired phenomena being initiated. The concept of 'Big Data' can be implemented by combining the machine data with the lubricant data [23]. The presence of wear debris, soot production, change in oil viscosity etc. can indicate if any corrective action needs to be taken. In fact, for tribology to be ready for industry 4.0, should include shorter lubricant development time, reduced number of trials, lubricant performance prediction through chemical and physical modelling and simulations.

## 1.8 Closure

Tribology though not in a formal way has been part of human civilisation almost since its inception. Initially, it was practiced just as a means of solving the problems of friction. But gradually humankind realized the potential of tribology as its various aspects began to unfold through either independent research or finding solution to a particular problem. Industrial revolutions definitely played a part in the development of tribology as a subject and benefits of the same has been reaped by the industries. The knowledge of tribology has now got an additional facet due to the present problems of energy conservation and climate change. Obviously, tribology has yet to offer lot more considering these aspects and the true potential of it can only be revealed by proper and wide application of it.

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