CHAPTER 1

INTRODUCTION

1.1 TRIBOLOGY

The term tribology is defined as the science and practice of interacting surfaces in a relative motion. It also includes the study and application of the principles of wear, friction and lubrication.

Etymology: The word tribology was derived from the Greek word ‘τρίβω’ (tribos) which means “rubbing” and the logy from ‘λογία’ (logia) which means “knowledge of” (Williams 2005).

Tribology was coined by the British physicist David Tabor (Field 2008) and also by Peter Jost in 1964, a lubrication expert who noticed the effect with increasing friction on machines and started the new set discipline called tribology (Mitchell and Luke 2012). The disciplines of tribology are relatively recent and were probably initiated in the year 1966 by Peter Jost, England.

1.1.1 Disciplines of Tribology

Tribology has three major parts namely, (a) Friction (b) Wear and (c) Lubrication. It requires knowledge from various subjects such as Physics, Chemistry, Mathematics, Thermodynamics, Heat Transfer, Material Science, etc., to understand the tribological behaviours. Many failures of metals occur
more due to tribological problem than to mechanical problems such as fracture, plastic deformation and fatigue.

Figure 1.1 Disciplines of tribology

Figure 1.1 shows the interaction between friction, wear and lubrication and the intersection portion is considered as the multi-disciplinary concept of tribology. Thus, for any tribology study, the examination of its friction, wear and lubrication mechanisms needs to be considered.

1.2 FRICtION

Friction is defined as the force offered against the motion of a solid object which is moved over the surface of another object (Bhushan 1999 and Singer 1992).

The classic rules of sliding friction were discovered by Leonardo da Vinci, but remained unpublished (Dowson and Duncan 1997, Armstrong-Helouvy and Brian 1991). In 1699, Guillaume Amontons rediscovered the nature of friction, in terms of surface irregularities and the force required to raise the weight pressing the surfaces together. This work was extended by
Belidor. In 1750, Leonhard Euler derived the angle of repose of a weight on an inclined plane and distinguished static and kinetic friction.

In 1785, Charles Augustin de Coulomb investigated the factors influencing friction; they are,

1. The nature of the materials in contact and their surface coatings,
2. The extent of the surface area,
3. The normal load and
4. The length of time that the surfaces remained in contact.

He also considered the influence of sliding velocity, temperature and humidity. The characteristic of static and kinetic friction is stated in Coulomb's friction law.

**First law:** Friction is independent of the normal load.

**Second law:** The friction force is independent of the apparent area of contact between the contact surfaces.

**Third law:** The kinetic friction force is independent of the sliding velocity, once motion starts.

### 1.2.1 Theories of Friction

**Adhesion theory:** Adhesion is a surface interaction phenomenon and is the ability of contacting bodies to resist tensile forces after being pressed together. A strong adhesive junction (Figure 1.2) is formed when two precise clean surfaces are pressed together. No inter-diffusion or recrystallization of metal atoms takes place at the junction, as is done in a
cold condition and the condition predominating at the interface of the junction is like “cold welding”.

Figure 1.2 An adhesion junction (Buckley 1981)

Asperity interlocking theory: In engineering surfaces, it is practically difficult to get a perfectly smooth and flat surface. It has asperities and waviness. When two surfaces are placed in contact, they touch only at discrete points called asperities. The applied load is supported by the deformation of the contacting asperities. Among many investigators, Coulomb (1736-1803) was perhaps the first to develop a model, to understand the friction due to the interlocking of asperities. During sliding, the plastic deformations of softer asperities have to take place by the application of force. This leads to frictional resistance (Figure 1.3).

Figure 1.3 Asperity interlocking surfaces (Bowden and Tabor 1973)
However, this theory is not recognized very well, as it is observed that the $\mu$ increases when the surface becomes very smooth, but according to asperity interlocking theory, the $\mu$ should decrease as the mountains and valleys would be very small and must need very small force for their plastic deformation. This theory is yet again contrary to the assumption. For a very smooth surface, the real contact area becomes more (equal to the apparent area) and hence the friction coefficient increases (Figure 1.4).

![Figure 1.4 Effect of surface roughness on coefficient of friction (Bowden and Tabor 1950)](image)

**Molecular attraction theory:** The investigator Hardy (1928) was the first to state that friction is because of the molecular attraction. The origin of this theory is the partial irreversibility of the bonding force among the atoms. Such molecular attraction works over short distances and thus discriminates between the real area of contact and apparent area of contact. Still, this theory may perhaps be considered to have a certain scope as the “adhesion theory”.

**Stick-slip theory:** This may also be considered as an alternative description of the adhesion theory. The assumption is that one surface rests over another at junctions, as shown in Figure 1.5. As soon as one surface
starts sliding over another, a rise in temperature occurs at these junctions; this results in local welding at the point of contact (junction). Therefore, it leads to a resistance to motion, i.e., friction. Sliding occurs on account of applied force, by the tearing apart of these welds. Proximately, after this sliding, local welding takes place on another set of junctions, which are again torn to enable sliding and such sticking and slipping (sliding) continues.

Figure 1.5 A two adhesive junction (Bowden and Tabor 1950)

1.3 WEAR

In any tribological system, when two solid surfaces are in contact, there is damage to the surface and/or subsurface. Wear is erosion or the sideways displacement of the material from its original position on a solid surface, performed by the action of another surface.

Wear is correlated to interactions between surfaces and more precisely, the removal and deformation of a material on a surface as a result of the mechanical action of the opposite surface (Rabinowicz 1995).

Wear can also be defined as a process, where interaction between two surfaces or bounding faces of solids within the working environment
results in the dimensional loss of one solid, with or without any actual decoupling and loss of material. Aspects of the working environment which affect wear include not only loads and features such as unidirectional sliding, reciprocating, rolling, impact loads, speed and temperature.

1.3.1 Types of Wear

(a) Adhesive wear
(b) Abrasive wear
(c) Erosive wear
(d) Fretting wear
(e) Corrosive wear

**Adhesive wear:** Adhesive wear is due to the strong adhesive force; and the arrangement is when the atoms come into close contact, as shown in Figure 1.6. In the course of sliding, a small patch of one of the surfaces comes into close contact with a small patch of the other surface and if this bond is strong, the contact is broken, not from the interface of the two patches but from within one of the materials (Buckley 1981). Figure 1.6 shows that the junction breaks not from path 1 but from path 2. This happens when the force required to break through the interface of the material (path 1) is greater than the force required for breaking through some continuous surface inside one of the materials (path 2).

The adhesive wear rate is rather independent of the surface roughness. Adhesive wear can occur on both rough and smooth surfaces, as the formation of adhesive junctions depends more on the cleanliness of the
two surfaces. It is also observed that the wear rate decreases with an increase in the ratio of the hardness of the two materials.

![Image](image.png)

**Figure 1.6 Adhesive wear of a junction (Buckley 1981)**

**Laws governing wear**

The volume of wear mass loss is believed to be governed by the following laws:

1. The volume of wear mass loss is directly proportional to the applied load.
2. The volume of wear mass loss is directly proportional to the sliding distance.
3. The volume of wear mass loss is inversely proportional to the hardness of the surface being worn out.
4. Wear rate is independent of the apparent area, but is dependent on the real area of contact area.

**Abrasive wear:** Abrasive wear occurs due to a hard rough surface sliding along a soft surface. It results in digging into it and ploughing a series of grooves. The materials, originally in the grooves, usually come out in the form of loose fragments. This is well-known as two body wear.
Abrasive wear also occurs when hard abrasive particles are introduced between two sliding surfaces and these particles abrade either or both materials. The mechanism is that an abrasive particle adheres temporarily to one of the sliding surfaces or, else, gets embedded in it and plows out grooves in the other surface. This form of wear is called as abrasive wear.

Two body wear does not take place when the hard sliding surfaces are smooth. Likewise, three body wear does not normally occur when the particles, introduced in between the sliding surfaces, are small or when they are softer than the sliding materials. Conversely, once the sliding has started, the wear debris, initially produced, frequently gets hardened by oxidation etc. and aggravates the abrasive wear subsequently. But once the sliding system comprises of a restricted quantity of abrasive particles, which were used numerous times as the sliding continues, the wear rate likely falls as the abrasive particles get smoother and smaller. An alternative cause for the decrease in the wear rate in such cases or further cases of unceasing abrasion is that the loose wear particles clog the abrasive surfaces and also the abrasive surfaces get blunt after some wear. Figure 1.7 shows both these aspects, i.e., clogging and abrasive surfaces by wear debris and also blunting of the abrasive surfaces.

![Figure 1.7 Magnified appearance of blunting and clogging of abrasive surfaces (Sushil 2001)](image)
**Erosive wear:** Wear due to the mechanical interaction between a solid surface and a fluid, or impinging liquid or solid particles is called erosive wear. When particles with some velocity are impacted on the surface of metal, pits and large scale subsurface deformations occur on the metal surface. The best example is when rain droplets with different velocities hit the normal earth’s surface; they remove the surface and cause erosive wear.

**Fretting wear:** Wear due to the small amplitude of oscillatory or reciprocating movement between two surfaces is known as fretting wear. It is a two step mechanism. Initially, adhesive wear occurs due to the rubbing of the two surfaces and then they become oxidized due to the large quantity of energy stored in the wear particles.

**Fatigue/Delamination wear:** Wear caused by fracture arising from surface fatigue due to cyclic loading is called Fatigue/Delamination wear. It results in a series of pits or voids. It usually occurs in rolling or sliding contact bodies, such as bearings, etc. After repeated cyclic loading, a crack is observed on the subsurface or the surface. The subsurface cracks propagate, connect with other cracks, reach the surface and generate wear particles. Similarly, the surface cracks move downward into the bulk, connect with other cracks and liberate a wear particle. The crack propagation is influenced by a number of factors. The relative humidity in the air is one of the important factors. It has been experimentally reported, that the crack growth occurs rapidly in a high moisture environment rather than in dry air.

**Corrosive/Oxidative wear:** Corrosive wear occurs when sliding takes place in a corrosive or oxidative environment. During dry sliding also, the oxygen from the normal environment or other gases present in the environment can react with the solid surface. The excessive presence of anti-wear additives or other chemical agents can also cause corrosive wear.
At elevated temperatures, oxygen can interact with a sliding surface and form oxides called oxidative wear.

1.4 LUBRICATION

Lubrication is the process, or technique employed to decrease the wear of one or both surfaces, in close vicinity and moving relative to each other, by interposing a substance called lubricant between the surfaces, to transfer or aid to transfer the load between the opposing surfaces. The interposed lubricant film can be a solid, solid/liquid dispersion, a liquid, liquid/liquid dispersion or, exceptionally, a gas.

Sufficient lubrication permits a smooth continuous operation of equipment, resulting in only mild wear and without extreme stresses or seizures at the bearings. While the lubrication breaks down, the metal or other components can rub detrimentally over each other, producing critical damage, heat and failure.

In common cases, the applied load are carried by the pressure generated within the fluid, due to the frictional viscous resistance to motion of the lubricating fluid between the surfaces.

1.4.1 Types of lubrication

(a) Fluid film lubrication: It is the lubrication regime in which through viscous forces, the load is entirely maintained by the lubricant within the space or gap between the parts in motion relative to one another (the lubricated conjunction) and solid-solid contact is avoided.
i. **Hydrostatic lubrication:** It is when an external pressure is applied to the lubricant in the bearing, to preserve the fluid lubricant film, which would otherwise be squeezed out.

ii. **Hydrodynamic lubrication:** It is where the motion of the contacting surfaces and the precise design of the bearing are used to pump the lubricant around the bearing to preserve the lubricating film.

(b) **Elastohydrodynamic lubrication:** The opposing surfaces are separated, but there occurs some interaction between the elevated solid structures called asperities and there is an elastic deformation on the contacting surface, increasing the load-bearing area whereby the viscous resistance of the lubricant becomes capable of supporting the load.

(c) **Boundary lubrication:** The bodies come into closer contact at their asperities; the heat established by the local pressure causes a condition which is called stick-slip and some asperities break off.

At elevated temperatures and pressure conditions, chemically reactive constituents of the lubricant react with the contact surface, establishing a highly resistant tenacious layer or film, on the moving solid surfaces (boundary film), which is capable of supporting the load and major wear or breakdown is avoided. Boundary lubrication is also defined as the regime, in which the load is supported by the surface asperities rather than by the lubricant. It is also called boundary film lubrication.

Lubrication is vital for the precise operation of mechanical systems, such as pistons, pumps, cams, bearings, turbines and cutting tools, where
without lubrication the pressure between the surfaces in close vicinity would produce enough heat for rapid surface damage and which in a coarsened condition might exactly weld the surfaces together, producing seizure.

1.5 COMPOSITES

The term composite is used for describing materials which are semi-homogeneous and have superior mechanical and physical properties than those of their components. The matrix of a composite can be a metal, ceramic or polymer. Furthermore, composites can be grouped on the basis of the reinforcements provided (Schoutens and Tempo 1982).

1.5.1 Types of Composites

a) Fiber composites
b) Particle composites
c) Flake composites
d) Laminar or layered composites
e) Filled composites

1.5.2 Classification of Composite Materials

Metal Matrix Composites: The matrix phase for a MMC is a metal often which is ductile. MMCs are manufactured with aims to have high strength to weight ratio, high resistance to abrasion and corrosion, resistance to creep, good dimensional stability and high temperature operability. MMCs are used in industries like automobile and aerospace. Mostly, aluminium is used as the metal matrix.

Ceramic Matrix Composites (CMCs): This class of composites contains ceramic materials as matrix phase. CMCs are developed primarily to
improve the fracture toughness of ceramic materials. This makes the CMCs to be used in extreme environments of high temperature and stress state. The dispersed phase plays a major role in preventing the propagation of cracks. This dispersed phase can be fibers, particles or whiskers.

**Polymer Matrix Composites (PMCs):** They contain polymer as the matrix phase and fibers such as E-glass, carbon or aramid as the reinforcing phase. The different varieties of PMC mostly used are Glass Fiber-Reinforced Polymer (GFRP) composites, Carbon Fiber-Reinforced Polymer (CFRP) composites and aramid fiber-reinforced polymer composites. The most commonly used polymers as matrix are vinyl esters and polyesters.

### 1.5.3 Manufacturing Methods of Composites

**Powder blending and consolidation:** The frequently used technique for the preparation of discontinuous reinforced MMCs is the powder blending and consolidation. In this process, powders of the metallic matrix and reinforcement are first blended and fed into a mold of the desired shape. Blending can be carried out dry or in liquid suspension. Pressure is then applied to further compact the powder (cold pressing). The compact is then heated to a temperature, which is below the melting point but sufficient to develop significant solid state diffusion (sintering). After blending, the mixture can be processed by hot pressing or Hot Isostatic Pressing (HIP) to achieve high density. The consolidated composite is then available for secondary processing. Attaining a homogeneous mixture during blending is a critical factor because the discontinuous reinforcement tends to persist as agglomerates, with interstitial spaces too small for the penetration of the matrix particles.
**Consolidation diffusion bonding:** This technique is typically used to manufacture fiber reinforced MMCs from sheets, foils, powder, powder tape or wire of matrix material.

The techniques of assembling reinforcement fibers and matrix alloys are determined by the fiber type and fiber array preform method. In the case of monofilaments, such as SiC and B₄C, parallel arrays with controlled fiber-to-fiber spacing are generated using drum winding, weaving with metallic ribbons, or feeding one or more filaments into a continuous process. Tow based fibers, such as alumina or graphite is usually drum wound for a continuous payout.

Matrix materials can be supplied to the composite assembly as separate constituents (e.g., foils, powder mat or tape, wires etc.), or applied directly to the fiber array (e.g., vapour deposition, plasma spray). The composite elements are assembled by layering the fiber array and matrix plies, to realize a predetermined fiber orientation and composite thickness.

Composite consolidation is achieved by applying high pressure, in a direction normal to the ply surfaces and a temperature adequate to produce atomic diffusion of the applicable matrix alloy. This method is performed in a vacuum environment.

**Vapour deposition:** Prominent among the vapour deposition techniques for the fabrication of MMCs is Electron Beam/Physical Vapour Deposition (EB/PVD). This process comprises of a continuous passage of fiber through a region of high partial vapour pressure of the metal to be deposited, where condensation takes place so as to produce a moderately thick coating on the fiber. The vapour is produced by aiming a high power (10kW) electron beam onto the end of a solid bar feedstock. A unique advantage of this technique is that an extensive choice of alloy compositions can be used.
An additional advantage worth note is that, there is a little or no mechanical disturbance of the interfacial region, which may be rather important when the fibers have a diffusion barrier layer. Composite fabrication is typically completed by assembling the coated fibers into a bundle or array and consolidating in a hot press.

**Stir Casting:** Stir Casting is a liquid state technique of composite materials fabrication, in which a dispersed phase (ceramic particles, short fibers etc.,) is mixed with a molten matrix metal by means of mechanical stirring.

**Squeeze casting and squeeze infiltration:** In squeeze casting, a hydraulically triggered ram applies a low controlled pressure to the molten metal, to achieve infiltration of the preform without damaging it. Infiltration may or may not be vacuum assisted. Once infiltration is complete, high pressure is applied to remove the shrinkage porosity, which can occur when the liquid metal contracts as it transforms into the solid state. This ample consolidation, or absence of porosity, endows the squeeze cast metal matrix composite materials with exceptional mechanical properties.

**Spray deposition:** Numerous methods have been developed under this classification, in which a stream of metal droplets impinges on a substrate in such a way as to construct a composite. If the reinforcement is particulate, it can be fed into the spray. The matrix spray can be applied to an array of fibers. The methods used fall into two discrete classes, depending on whether the droplet stream is produced from the molten bath, or by continuous feeding of cold metal into a zone of rapid heat injection.

**Slurry casting (Compo casting):** Liquid metal is stirred as solid reinforcement particles are added to the melt to produce slurry. Stirring continues as the melt is cooled till the metal itself becomes semi-solid and
traps the reinforcement particles in a uniform dispersion. Further cooling and solidification then takes place without additional stirring. The slurry may be moved directly to a shaped mold prior to complete solidification, or it may be allowed to solidify in a billet or rod shape, so that it can be reheated to the slurry form for further processing by techniques, such as die casting.

**Reactive processing (In-Situ composites):** There are several different processes that would fall under this category. Directional solidification of eutectics in which one of the phases solidifies in the form of fibers is one such process. The inherent limitations in the nature and volume fraction of the reinforcement and the morphological instabilities associated with thermal gradients have resulted in a decrease in the interest in these types of composites. Exothermic reactions, such as directed metal oxidation, are one family of processes for the production of in-situ composites. The foremost advantage of this class of composites is that the in-situ reaction products are thermodynamically stable.

### 1.6 ALUMINIUM ALLOY

Aluminium (or aluminium) is a chemical element in the boron group, with the symbol Al and atomic number 13. It is silvery white and it is not soluble in water under normal circumstances. Aluminium is the third most abundant element (after oxygen and silicon) (Degarmo et al 1997, 2003). It makes up about 8% by weight of the Earth's solid surface. Aluminium metal is so chemically reactive that native specimens are rare and limited to extreme reducing environments. Instead, it is found combined in over 270 different minerals. The principal ore of aluminium is bauxite. Aluminium is significant for its low density and ability to resist corrosion due to the phenomenon of passivation.
Structural components made from aluminium and its alloys are vital to the aerospace industry and are important in other areas of transportation and structural materials. The most useful compounds of aluminium, at least on a weight basis, are the oxides and sulfates. Owing to their prevalence, the potential beneficial biological roles of aluminium compounds are of continuing interest.

1.6.1 History of Aluminium Alloy

According to Jefferson Lab, “Scientists suspected that an unknown metal existed in alum as early as 1787, but they did not have a way to extract it until 1825”. Hans Christian Oersted, a Danish chemist, was the first to produce tiny amounts of aluminium. Two years later, Friedrich Wohler, a German chemist, developed a different way to obtain the metal. By 1845, he was able to produce samples large enough to determine some of aluminium's basic properties. Wohler's method was improved in 1854 by Henri Etienne Sainte-Claire Deville, a French chemist. Deville's process led to the commercial production of aluminium. As a result, the price of the metal dropped in 1859. In 1889, Charles Martin Hall patented an inexpensive method for the production of aluminium, which brought the metal into wide commercial use.

According to Jefferson Lab, “Although aluminium is the most abundant metal in the earth's crust, it is never found free in nature. All of the earth's aluminium has combined with other elements to form compounds. One of the most common compounds is Potassium aluminium sulfate. About 8.2% of the earth's crust is composed of aluminium”.
### 1.6.2 Temper designation

The definitions for the tempers are shown in Table 1.1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>As fabricated</td>
</tr>
<tr>
<td>H</td>
<td>Strain hardened (cold worked) with or without thermal treatment</td>
</tr>
<tr>
<td>H1</td>
<td>Strain hardened without thermal treatment</td>
</tr>
<tr>
<td>H2</td>
<td>Strain hardened and partially annealed</td>
</tr>
<tr>
<td>H3</td>
<td>Strain hardened and stabilized by low temperature heating</td>
</tr>
<tr>
<td></td>
<td>Second digit for H series - A second digit denotes the degree of hardness</td>
</tr>
<tr>
<td>HX2</td>
<td>1/4 hard</td>
</tr>
<tr>
<td>HX4</td>
<td>1/2 hard</td>
</tr>
<tr>
<td>HX6</td>
<td>3/4 hard</td>
</tr>
<tr>
<td>HX8</td>
<td>full hard</td>
</tr>
<tr>
<td>HX9</td>
<td>extra hard</td>
</tr>
<tr>
<td>O</td>
<td>Full soft (annealed)</td>
</tr>
<tr>
<td>T</td>
<td>Heat treated to produce stable tempers</td>
</tr>
<tr>
<td>T1</td>
<td>Cooled from hot working and naturally aged (at room temperature)</td>
</tr>
<tr>
<td>T2</td>
<td>Cooled from hot working, cold-worked and naturally aged</td>
</tr>
<tr>
<td>T3</td>
<td>Solution heat treated and cold worked</td>
</tr>
<tr>
<td>T4</td>
<td>Solution heat treated and naturally aged</td>
</tr>
<tr>
<td>T5</td>
<td>Cooled from hot working and artificially aged</td>
</tr>
<tr>
<td>T51</td>
<td>Stress relieved by stretching</td>
</tr>
<tr>
<td>T510</td>
<td>No further straightening after stretching</td>
</tr>
<tr>
<td>T511</td>
<td>Minor straightening after stretching</td>
</tr>
<tr>
<td>T52</td>
<td>Stress relieved by thermal treatment</td>
</tr>
<tr>
<td>T6</td>
<td>Solution heat treated and artificially aged</td>
</tr>
<tr>
<td>T7</td>
<td>Solution heat treated and stabilized</td>
</tr>
<tr>
<td>T8</td>
<td>Solution heat treated, cold worked and artificially aged</td>
</tr>
<tr>
<td>T9</td>
<td>Solution heat treated, artificially aged and cold worked</td>
</tr>
<tr>
<td>T10</td>
<td>Cooled from hot working, cold-worked and artificially aged</td>
</tr>
<tr>
<td>W</td>
<td>W is a relatively soft intermediary designation that is applied after heat treatment and before aging is completed. The ‘-W’ condition can be extended at extremely low temperatures but not indefinitely and depending on the material will typically last no longer than 15 minutes at ambient temperatures. Solution heat treated only.</td>
</tr>
</tbody>
</table>
1.6.3 Wrought Alloys

The International Alloy Designation System (IADS) is the utmost widely accepted naming scheme for wrought alloys. Each alloy is given a four digit number, where the first digit indicates the major alloying elements.

1. 1000 series are principally pure aluminium with a minimum of 99% aluminium content by weight and can be work hardened.

2. 2000 series are alloyed with copper and can be precipitation hardened to strengths comparable to steel. Formerly referred to as duralumin, they were once the most common aerospace alloys, but were susceptible to stress corrosion cracking and are increasingly replaced by 7000 series in new designs.

3. 3000 series are alloyed with manganese and can be work hardened.

4. 4000 series are alloyed with silicon. They are also known as silumin.

5. 5000 series are alloyed with magnesium.

6. 6000 series are alloyed with magnesium and silicon, are easy to machine and can be precipitation hardened.

7. 7000 series are alloyed with zinc and can be precipitation hardened to the highest strengths of any aluminium alloy.

8. 8000 series is a category mainly used for lithium alloys.
1.6.4 Factors Affecting Wear of Aluminium Based Composite Materials

The major tribological parameters that control the friction and wear performance of reinforced AMCs are mechanical and physical features, extrinsic to the material undergoing surface interactions such as the effect of load normal to the tribo-contact, the sliding velocity, the sliding distance, the reinforcement orientation, the environment, the temperature and the surface finish and the counterpart and material factors intrinsic to the material undergoing surface interaction, such as the reinforcement type, size, shape and distribution of the reinforcement, the matrix microstructure and the reinforcement volume fraction.

While investigating the wear of particle reinforced MMCs under different applied load conditions, three different wear regimes were identified. At low load (regime I), the particles support the applied load in which the wear resistances of the MMCs are in the order of a magnitude better than Al-alloy. At regime II, the wear rates of the MMCs and Al-alloy were similar. At high load and the transition to severe wear (regime III), the surface temperatures exceed a critical value. With regard to the material factors, the volume fraction of reinforcement \( (v_r) \) has the strongest effect on the wear resistance.

However, the variations in the wear rates of the MMCs as functions of \( v_r \) are affected by the shape and size of the whiskers, fibers and particles used for reinforcement. Additionally, the effective \( v_r \), at which the wear rate reaches its minimum value, is considerably different depending on the kind of reinforcement and matrix material as well as on the sliding conditions.

Hence, it is difficult to select the type of reinforcement and volume fraction that would give the optimum wear properties. Many investigators
carried out experiments on the wear behaviour of MMCs against different counter surfaces under various test conditions.

1.6.5 History of AA 6061

AA 6061 is a precipitation hardening aluminium alloy, containing magnesium and silicon as its major alloying elements. Originally called "Alloy 61S" it was developed in 1935 (Robert Sanders 2001). It has good mechanical properties and exhibits good weldability. It is one of the most common alloys of aluminium for general purpose use. It is available in pre-tempered grades such as 6061-O and tempered grades such as 6061-T6 and 6061-T651.

1.6.6 Properties of AA 6061

The mechanical properties of AA 6061 depend significantly on the temper, or heat treatment of the material. The young's modulus is 69GPa regardless of temper. The ultimate tensile strength is 300-310MPa and yield strength is 241-275MPa.

1.6.7 Applications of AA 6061

Essentially in construction of aircraft structures, such as wings and fuselages, more frequently in homebuilt aircraft than commercial or military aircraft. AA 6061 is more easily worked and remains resistant to corrosion even when the surface is abraded, which is usually used with a thin Alclad coating for corrosion resistance.

1.6.8 History of AA 7075

7075 is an aluminium alloy, with zinc as the alloying element. It is strong, with good fatigue strength and average machinability, but is not weldable and has less resistance to corrosion than many other alloys.
Its relatively high cost limits its use to applications, where cheaper alloys are not suitable.

The first AA 7075 was developed by the Japanese company Sumitomo Metal in 1936. AA 7075 was used for the Zero fighter's air frame of the Imperial Japanese Navy in pre-war times.

1.6.9 Applications of AA 7075

a) AA 7075 is extensively used for the construction of aircraft structures, such as wings and fuselages. Its strength and light weight are also desirable in other fields.

b) Rock climbing equipment and bicycle components are commonly made from 7075 aluminium alloy. The bicycle industry also uses 7005 and 6061 aluminium alloys. Hobby grade R/Cs commonly use 7075-T6 and 6061 for chassis plates.

1.7 GRAPHITE

The mineral graphite is an allotrope of carbon. It was named by Abraham Gottlob Werner in 1789 from the Ancient Greek grapho, “to draw/write” (Henry George Liddell and Robert Scott 1940), for its use in pencils, where it is commonly called lead. Unlike diamond (another carbon allotrope), graphite is an electrical conductor, a semi-metal. It is consequently, useful in such applications as arc lamp electrodes. Graphite is the most stable form of carbon under standard conditions. Therefore, it is used in thermo-chemistry as the standard state for defining the heat of formation of carbon compounds. Graphite may be considered the highest grade of coal, just above anthracite and alternatively called meta-anthracite, although it is not normally used as fuel because it is difficult to ignite.
There are three principal types of natural graphite, each occurring in different types of ore deposit;

1. Crystalline flake graphite (or flake graphite for short) occurs as isolated, flat, plate-like particles with hexagonal edges.

2. Amorphous graphite occurs as fine particles and is the result of the thermal metamorphism of coal, the last stage of coalification and is sometimes called meta-anthracite. Very fine flake graphite is sometimes called amorphous in trade.

3. Lump graphite (also called vein graphite) occurs in fissure veins or fractures and appears as massive platy intergrowths of fibrous or acicular crystalline aggregates and is probably hydrothermal in origin.

Graphite has a layered, planar structure. In each layer, the carbon atoms are arranged in a hexagonal lattice, with a separation of 0.142nm and the distance between the planes is 0.335nm (Delhaes 2001). The two known forms of graphite, alpha (hexagonal) and beta (rhombohedral), have very similar physical properties (except that the graphene layers stack slightly differently) (Cousins 2003). The hexagonal graphite may be either flat or buckled (Wyckoff 1963). The alpha form can be converted to the beta form through mechanical treatment and the beta form reverts to the alpha form when it is heated above 1300 °C (Nic et al 2006). The layering contributes to its lower density.

Graphite and graphite powder are valued in industrial applications for their self-lubricating and dry lubricating properties. There is a common belief that graphite’s lubricating properties are solely due to the loose inter-lamellar coupling between the sheets in the structure.
1.8 ALUMINIUM OXIDE

The chemical formula of aluminium oxide is Al₂O₃. It is commonly referred to as alumina, or corundum in its crystalline form, as well as many other names, reflecting its wide spread occurrence in nature and industry. Alumina (Al₂O₃) is the most cost effective and widely used material in the family of engineering ceramics. Table 1.2 shows the properties of Al₂O₃.

**Characteristics of Al₂O₃**

- Hard and wear resistant.
- Good thermal conductivity.
- Excellent size and shape capability.
- High strength and stiffness.

**Table 1.2 Properties of aluminium oxide**

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular formula</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>Molar mass</td>
<td>101.96 g/mol</td>
</tr>
<tr>
<td>Appearance</td>
<td>white solid</td>
</tr>
<tr>
<td>Odor</td>
<td>Odorless</td>
</tr>
<tr>
<td>Density</td>
<td>3.95–4.1 g/cm³</td>
</tr>
<tr>
<td>Melting point</td>
<td>2072 °C</td>
</tr>
<tr>
<td>Boiling point</td>
<td>2977 °C</td>
</tr>
<tr>
<td>Hardness</td>
<td>1175 Kg/mm²</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.21</td>
</tr>
</tbody>
</table>
1.9 BORON CARBIDE

Boron carbide (B\textsubscript{4}C) is an extremely hard boron-carbon ceramic material used in tank armor, bullet proof vests and numerous industrial applications. It is one of the hardest materials known, behind cubic boron nitride and diamond.

Boron carbide was discovered in the 19th century as a by-product of reactions involving metal borides; however, its chemical formula was unknown. It was not until the 1930s that the chemical composition was estimated as B\textsubscript{4}C (Ridgway and Ramond 1934). There remained, however, a controversy as to whether or not the material had this exact 4:1 stoichiometry. The B\textsubscript{12} structural unit, the chemical formula of “ideal” boron carbide is often written not as B\textsubscript{4}C, but as B\textsubscript{12}C\textsubscript{3} and the carbon deficiency of boron carbide is described in terms of a combination of the B\textsubscript{12}C\textsubscript{3} and B\textsubscript{12}C\textsubscript{2} units (Musiri 2007, Patnaik 2002).

Boron carbide is known as a robust material having high hardness, high cross section for absorption of neutrons (i.e. good shielding properties against neutrons), stability to ionizing radiation (Vladislav 2011) and most chemicals. Its fracture toughness (3.5MPa·m\textsuperscript{1/2}) approach the corresponding values of diamond (5.3MPa·m\textsuperscript{1/2}) (Zhang et al 2001).

1.10 SUMMARY

In the current chapter, the factors associated with tribology were studied in detail. The composites and their nature and various reinforcements with specific reference to metal matrix composites were studied. The aluminium based MMCs and their various types including possible routes of manufacturing with applications were also studied.