CHAPTER 1

INTRODUCTION

1.1 TRIBOLOGY

Tribology is a branch of science related to the terms such as wear, friction and lubrication. Tribology is defined as the science and technology of interacting surfaces in relative motion and the practices related there to (Jost 1966).

Tribology is an important phenomenon related to machineries in industries. Several tribological machine components such as brakes, clutches, bearings, bushes, gears, cams, seals, driving wheels, bolts and nuts (Hutching 1992) are subjected to friction and wear. The tribology parameters such as friction and wear affect the life of the machine parts and also reduce their efficiency. Hence, the investigation in tribology would reveal results that would enable the machines to improve their performance. The invention of new materials to face the above criteria by combining the metals and its alloys, ceramics, solid lubricants, particulates and polymers is a good practice being adopted by the various researchers. In this group, fiber reinforced polymer (FRP) composites are widely used in several structural applications in the field of automotive, aerospace and chemical industries because of their superior properties such as high strength to weight ratio, stiffness to weight ratio and improved corrosion resistance. FRP composite materials contain self lubricating property and minimum noise.
1.2 COMPOSITE MATERIALS

Composite materials are an amalgamation of materials of any two or more chemically distinct and insoluble phases with properties and structural performance superior to those constituents acting independently. The characteristics of the composite materials, as spelt out by Broughtman and Krock (1967) are as follows:

1. Composite materials must be man-made.

2. Composite material must be a combination of at least two chemically distinct materials with a distinct interface separating the components.

3. Separate materials forming the composite must be combined three dimensionally.

4. Composite material should be created to obtain those properties which cannot be achieved by any of these components acting independently.

Composite materials are generally prepared by each of the three major groups of materials such as metals, ceramics and polymers. Most composite materials are developed to improve the mechanical properties such as stiffness, toughness and hardness. Composites also possess other superior properties like high strength, light weight, wear resistance etc. Normally, composite materials consists of a minimum two phases namely, the matrix phase and the reinforcement phase (Autar Kaw 1996). The matrix phase consists of a monolithic material in which the reinforcement is entrenched and is continuous. The primary functions of the matrix phase are to transfer and distribute the load between the reinforcing phases. Matrices may be metal, ceramics or polymer. The matrix acts as a barrier to protect any environmental or mechanical degradation caused by factors such as abrasion or corrosion.
Reinforcement phases are either in continuous or discontinuous form. It possesses superior mechanical properties. Discontinuous reinforcement consists of whiskers, particles or short fibers with an isotropic behavior. The continuous reinforcement contains wires or fibers with anisotropic properties which are implanted in the matrix in a particular direction. The behavior of composites depends upon the matrix and reinforcement type, size and shape with quantity of reinforcement and bonding between the matrix with reinforcement.

Advanced composites are those composite materials which are traditionally used in aerospace industries. These composites have the reinforcements of thin fiber in the matrix materials such as epoxy and aluminum. Graphite/epoxy, boron/aluminum are some of the examples of these composites.

### 1.3 CLASSIFICATION OF COMPOSITE MATERIALS

Composite materials are being developed in huge number to cater to various applications. Even though the composites are classified for the purpose of ease of identification, the basic classification can be sketched as shown in Figure 1.1.

![Figure 1.1 Classification of composite materials](image-url)
1.3.1 Composites based on Reinforcement

Dispersion strengthened composites consist of fine dispersion in matrix and the matrix acts as the load-carrying ingredient. The fine dispersion is present to hold up the motion of metal matrix dislocations. The matrix will be strengthened or reinforced in proportion to the effectiveness of the dispersion as a barrier to the motion of these dislocations. Particle-reinforced composites consists of a matrix phase in between the dispersion strengthened composite (where it is the major load carrying element), and fiber reinforcement composite (where its function is only transmit the load to the reinforcement fibers). In the particulate reinforcement type, both matrix and dispersed particles share the load. Fibrous reinforcement composites can be sub-classified as continuous fibrous and discontinuous fibrous-reinforced composites. In the continuous fibrous-reinforcement composite, the dispersion of fibers are uniform, continuous and unidirectional or bidirectional. Also they are firmly gripped by the matrix so that no slippage can occur at the interface between reinforcement and matrix. In the case of discontinuous fibrous composites, the short fibers have a random, parallel or any other preferred orientation in the matrix phase.

1.3.2 Composites based on Matrix Materials

1.3.2.1 Polymer matrix composites

Although polymers cannot boast of high mechanical properties such as strength, stiffness etc., when compared to metals and ceramics, they are still being used in any field of science and engineering. So, it is important to focus on generating Polymer Matrix Composites (PMCs) with superior mechanical properties such as high strength to weight ratio, high stiffness to weight ratio, good corrosion resistance. This can be obtained by reinforcing polymer matrix with the fibers and/or fillers. PMCs are advanced composite
materials consisting of polymers (matrix) such as epoxy, polyester, urethane, nylon etc., reinforced by thin diameter fibers such as glass, graphite, aramid, boron etc.,. Some of the examples of PMCs are glass/epoxy, graphite/epoxy composites. PMCs are manufactured by ease of processing. PMCs have low density and better thermal and electrical characteristics. So, PMCs are preferred for structural applications in the fields of automobile, aerospace, electrical and electronics. Also PMCs are five times stronger than steel. High strength, low cost, light weight and simple manufacturing methods are some of the advantages of PMCs materials.

1.3.2.2 Ceramic matrix composites

Ceramic Matrix Composites (CMCs) are consisting of fibers, fillers (particulates) or whiskers of ceramic materials surrounded in another ceramic matrix. Due to improved high-temperature properties, high strength, hardness and low density, CMCs are mainly used for higher temperature applications. Some of applications of CMCs are in the field of electronics; automobiles, aircraft gas turbine engines etc.,. Low ductility and toughness are some of the limitations of CMCs which accounts for its limited use. Since the processing path of CMCs involves high temperatures and thus, it is only suitable in case of high temperature applications. These are some of the obstacles which limit the use of CMCs. The best example for the CMCs is SiC/alumina composites used for the cutting tool inserts for machining of alloys.

1.3.2.3 Metal matrix composites

Metal Matrix Composites (MMCs) consist of the metallic matrix such as aluminium, copper, magnesium, titanium and zinc and its alloys which are reinforced with a metal or ceramic phase and are shaped as short fibers, particles platelets, continuously aligned fibers or whiskers. Graphite, Silicon carbide, alumina, fly ash and boron are some of reinforcements used
in the MMCs. It consists of superior mechanical properties such as light weight, higher strength and stiffness, improved compressive and shear strength, higher thermal conductivity, improved wear and erosion resistance. Due to these properties MMCs are widely used in the aerospace, automotive, electronics and industrial equipment production applications.

1.4 POLYMERS

Polymers are a large class of materials consisting of many molecules that can be linked together to form long chains by covalent bonds, thus gaining the name as macromolecules. Since it possess certain extraordinary properties, they play an essential and ubiquitous role in everyday life. The term Engineering polymers or called Engineering plastics are defined (Seymour 1990) as a synthetic polymer resin-based material which possess load bearing abilities and high performance characteristics. Thus, they have found wide applications such as metals or ceramics. Engineering plastics are classified as thermo plastics and thermo set plastics. The interest in engineering polymers is driven by qualities such as their manufacturability, recyclability, mechanical properties and low cost when compared to many alloys and ceramics. The polymer matrix composite materials have been created to improve the combination of mechanical characteristics such as strength, stiffness, and toughness, wear resistance under the ambient and high temperatures.

Polymers are classified in to two groups namely, elastomers and plastics. Elastomers are flexible or rubber like materials which can readily deformed and returned immediately in to their original shape and size when released from the load. Thus it is suitable for making seals. Synthetic and natural rubbers are some examples of this kind. Plastics are materials which can be shaped or moulded under suitable conditions of temperature and pressure and set in their final shape. When compared to elastomers, plastics have an
excellent stiffness though they do not have reversible elasticity. The properties and applications of important polymers are listed in Table 1.1.

**Table 1.1 Properties and applications of polymer materials**

<table>
<thead>
<tr>
<th>Material type</th>
<th>Major properties</th>
<th>Typical applications</th>
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<tbody>
<tr>
<td><strong>Thermosetting Polymers</strong></td>
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<tr>
<td>Polyesters (Unsaturated)</td>
<td>Rigid, tough, high strength, good creep resistance and fatigue resistance; chemical resistant and fire resistant, easy to process, heat-resistant up to 200°C, low cost</td>
<td>Used to make castings, fiber glass laminating resins, building panels, boat hulls, car bodies, vehicle caps, tanks and compressor</td>
</tr>
<tr>
<td>Epoxy resin</td>
<td>Rigid and strong, high tensile strength, good resistance to cracking, fatigue resistance, excellent adhesion properties; good electrical insulating properties</td>
<td>Used to make paints and coatings, adhesives, electrical components, pump components, wind mill structural construction applications, cardiac pacemakers and high strength applications</td>
</tr>
<tr>
<td>Vinyl ester</td>
<td>Improved mechanical properties, good impact and thermal shock resistance, rigid, translucent, good corrosion resistance and superior chemical resistance, low viscosity</td>
<td>Used to make chemical tanks, ducts, piping and process equipment</td>
</tr>
<tr>
<td>Phenolics</td>
<td>Brittle, opaque, good electrical and heat resistance; are resistant to deformation under load, cost effective</td>
<td>Used to make circuit boards, fuse boxes, lamp holders, bottle closures, toilet seats, thrust washers and laboratory countertops</td>
</tr>
<tr>
<td>Polyurethanes (cast elastomers)</td>
<td>Elastic, chemical and abrasion- resistant, good hardness</td>
<td>Used to make printing and industrial rollers, solid tiers, wheels and shoe heels</td>
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<table>
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<tr>
<th><strong>Thermoplastic polymers</strong></th>
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<tbody>
<tr>
<td>Polyethylene</td>
<td>Flexible, durable, waxy, weather-proof, easy to process, cost effective and possess excellent chemical resistance and low temperature toughness</td>
<td>Used to make squeeze bottles, toys, high frequency insulation, garment bags and chemical tank linings.</td>
</tr>
<tr>
<td>Nylon</td>
<td>Rigid, translucent, hard wearing, fatigue and creep resistant, resistant to fuels, oils and fats</td>
<td>Used to make bushings, gear wheels, zips, synthetic fibers, pressure tubing, fibers and filaments</td>
</tr>
<tr>
<td>Polyurethane (Thermoplastic)</td>
<td>Flexible, elastic, impermeable and wear resistant</td>
<td>Used to make foot ball boots, hammer heads, gaskets, noiseless gears and sprockets, O-rings, rollers and skate board wheels</td>
</tr>
<tr>
<td>Polyesters (Thermoplastic)</td>
<td>Rigid, clear, tough, posses good creep and fatigue resistance</td>
<td>Used to make the synthetic fibers, water bottles, parts for transformers, insulating tap, tarpaulins and LCDs</td>
</tr>
</tbody>
</table>
1.4.1 **Thermo Plastics**

Thermo plastics may be shaped or pressed in to molds, spun or cast from melts or dissolved in suitable solvents for later fashioning. Thermo plastics are repeatedly softened by heat and shaped. Thermoplastics are not cross linked, and have a very high molecular weight. It is anisotropic in nature and tends to change its shape under heat. It can also be classified as an amorphous or semi crystalline plastic. Some of the examples of thermoplastics are polyethylene, poly vinyl chloride, polystyrene, nylon, polycarbonate, poly methyl methacrylate and polypropylene.

1.4.2 **Thermosetting Plastics**

Thermo set plastics, which are densely cross-linked in the form of a network, degrade upon heating, while thermoplastics, which do not contain cross-links, melt upon heating. Thermosetting polymers are those resins which are set through a chemical reaction resulting in strong cross-linking by covalent intermolecular bonds of the structure. Once the chemical reaction is complete, the polymer becomes a hard, infusible, insoluble material which cannot be softened, melted or molded non-destructively. Thermosetting resins are isotropic in nature and they do not melt or change the shape during/after the application of heat. However, its stiffness reduces when subjected to heat. Epoxy resin provides better toughness and atmospheric weather- resistance, low moisture absorption and less shrinkage during curing than polyester and vinyl esters (Seymour 1990). Some examples of thermo-setting plastics are vinyl ester, polyester, epoxies, phenol formaldehyde, and melamine formaldehyde. The process of curing of the resins should either be carried out at room temperature or at elevated temperatures. Of all these, epoxy resin currently find applications in the advanced composite industries.
1.4.3 Epoxy Resin

Epoxy resins are most commonly used in Polymer matrix composite industries. Epoxy resin is a copolymer and is also known as Polyepoxide. Epoxy prepolymer contains epoxide end groups (Figure 1.2(a)) and pendant hydroxyl groups. Epoxy resin is produced during the reaction of epoxide resin with polyamine hardener. It is cured by adding curing agents at room temperature or at elevated temperature conditions. Epoxy molecules are expanded or cross-linked with other molecules to create new resin products, which find different applications. The most commonly used epoxies in the industries formed by the chemical reaction of epichlorohydrin and bisphenol-A (Lee and Neville 1967). Diglycidyl ether of bisphenol-A (DGEBA) is the most commonly used epoxy group for engineering application in industries. DGEBA is synthesized by reacting bisphenol-A with epichlorohydrin in the presence of a basic catalyst. DGEPA consists of two epoxide groups, one at each end of the molecule, as shown in Figure 1.2(b).

![Figure 1.2 (a) Epoxide group](image)

![Figure 1.2 (b) Preparation of epoxy resin](image)
The hardener consists of polyamine monomers which are mixed with the epoxide. The covalent bond is then created by the reaction of the amine group with epoxide group. During the chemical reaction, amine group react with an epoxide group. Thus the resulting polymer is heavily cross-linked, is rigid and strong. The hardener or curing agent is an important in the epoxies because these compounds control the reaction rate and also determine the performance characteristics of the finished parts. Since these compounds act as catalyst in the reaction, they must contain active sites on their molecules. Hence, the curing agents themselves act as the hardeners, catalysts as well as cross linking agents. Diethylene Triamine (DETA), Triethylene Tetramine (TETA) are frequently used in aromatic amines for curing at ambient temperature. Epoxy can be rigid or flexible with temperature and it can withstand up to 250 °C in various applications. Epoxies range from low viscosity to high molecular weight solids. Naturally, epoxies are high viscous liquids. Epoxy contains better stiffness and a higher tensile strength. Some of the major characteristics of the epoxy resin are rigid, tough, high mechanical properties, resistance to cracking and fatigue, excellent adhesion properties, minimum curing shrinkage rate, good electrical insulating properties and heat resistance.

The following are some of the main properties of epoxy, which is one of the most commonly used polymer matrix material.

i. High strength

ii. Low viscosity and low flow rates, which allow good wetting of fibers and prevent misalignment of fibers during processing

iii. Low volatility during cure

iv. Low shrink rates, which reduce the tendency of gaining large shear stresses of the bond between epoxy and its reinforcement
v. Availability in more than 20 grades to meet specific property and processing requirements

Due to these reasons, epoxy are used as paints and coatings, adhesives, matrix material for carbon fiber, glass fiber and kevlar reinforcement for composite materials in aerospace applications, high strength applications, electrical components, pump components, wind mill structural construction applications and cardiac pacemakers.

1.5 REINFORCEMENT MATERIALS

1.5.1 Kevlar Fiber

Kevlar fiber is a para aramid synthetic fiber which contains a high strength to weight ratio as that of glass fiber, even though its modulus is two times more than the glass fiber. It has improved stiffness, great dimensional stability and an exceptional impact resistance. It is used to manufacture bodies of the racing cars, helicopter rotor blades, cables and ropes, brake lining, drum heads, smart phones, shoes, tennis, badminton rockets and cricket bats.

1.5.2 Boron Fiber

Boron fiber is one of the most expensive reinforcing materials in structural applications. The high temperature boron is used to make the metal matrix composite, fighters, bomber aircrafts, helicopters and space shuttles. It is also used to make high end sporting equipment.

1.5.3 Glass Fiber

Glass fiber is one of the most commonly used reinforcing materials in polymer matrix composites. It consists of extremely fine fiber of glass.
Glass fiber possesses a high tensile strength and tensile modulus, high corrosion resistance, good insulating properties and low modulus compared to other polymer fibers. E-glass fibers are used to make electrical materials because it is an excellent insulator. C-glass is both chemical and corrosion-resistant fibers and it is used to make the pipes, storage tanks and chemical resistant equipment. Glass fibers are used to manufacture the automobile and truck body panels, boat hulls and marine structures, aircraft wings and fuselage sections, pipes, roofs, welding helmets, pressure vessels. The main disadvantages of the glass fibers are low stiffness, short fatigue life and high temperature sensitivity

1.5.4 Carbon Fiber

Carbon fibers are made of carbon crystals aligned in the long axis. The crystals of honeycomb shape organize themselves in long flatted ribbons. This honeycomb shaped crystal alignment provides strength to the carbon fiber and the ribbons are formed with long fibers. Carbon fibers are reinforcement materials for advanced composites with properties such as light weight and high strength. Carbon fibers have high specific strength i.e., high strength to weight ratio. The stiffness of the carbon fiber reinforced polymers is 5 times greater than that of the glass fabric and 3 times greater than the aluminium. Thus carbon fibers attain excellent fatigue resistance and tensile strength. Also, the specific strength (strength/density) and specific modulus (modulus/density) of carbon are higher than those of other comparable aerospace fibers and metallic alloys. This translates into greater weight savings thus resulting in improved performance, greater payloads, longer range, and fuel savings. The two advantageous factors of carbon fibers are; (i) manufacturing technology of carbon fiber is more conductive to mass production, when compared to other advanced fibers (ii) carbon fibers are more suitable for engineering applications which can be simply formed in to
usable composite physical and mechanical properties. In the molecular structure of the carbon, the graphitized atom provides self lubrication. Hence the carbon fiber itself acts as the self lubricant materials in the bearing applications. The two widely found applications of the carbon fibers are in the technology and medicine. While the former includes aerospace, nuclear engineering and in automotive engineering and the engineering components such as bearings, cams, gears, fan blades and automobile bodies, the later includes prostheses, surgery and x-ray equipment, implants and ligament repair.

The main characteristics of the carbon fibers are:

i. High strength to weight ratio
ii. Better stiffness
iii. Good rigidity
iv. Corrosion resistance and chemical inertness
v. Electrical conductivity
vi. Fatigue-resistance and self-lubrication properties
vii. High thermal conductivity and low coefficient of thermal expansion
viii. Efficient vibration damping, strength and toughness
ix. High dimensional stability and low abrasion
x. Textile processing ability
xi. Excellent fire resistance
xii. Cost effective manufacturing process
1.6 FILLER MATERIALS

Filler materials play an important role in strengthening mechanical properties, tribological characteristics and thermal stability of polymers. Filler materials when merged with the matrix materials and fibers provide ample resistance against the mechanical loading such as tensile and compressive loads, wear and abrasion. Some of the fillers used in these applications are namely ceramic hard particles, metallic powders and elastomeric fillers. These fillers which provide the effective mechanical and tribological improvements as analyzed by various researchers are $\text{Al}_2\text{O}_3, \text{MoS}_2, \text{CuS}, \text{ZrO}_2, \text{SiO}_2, \text{CuO}, \text{PbS}, \text{CaS}, \text{CaCO}_3$, clay, SiC and graphite. Briscoe et al. (1974) used the lead oxide and copper oxide as fillers. Srivastava and Pathak (1996) have used the graphite as fillers. Also, Li et al. (2004) used the MoS$_2$ as fillers. Some of the organic fillers mainly elastomers were utilized by the composite manufacturers. When compared to resin and reinforcements, fillers are inexpensive. Depending upon the material used, fillers can improve smoke and fire resistance, surface smoothness and water resistance in addition to providing with the mechanical and tribological properties.

1.7 HYBRID COMPOSITES

Some of desirable characteristics of composites are obtained by producing hybrid composites (ie,) the two or more than two different fibers/fillers are reinforced with in the same matrix. The behavior of hybrid composite is based on the weighed sum of the individual components, thus balancing the inherent advantages and disadvantages. Hybrid composites contain two or more types of fibers/fillers, with the advantages of one type of fiber/filler could complement with what lacks in the other. As a result, in cost and performance balance can be achieved through proper material design.
The properties of these composites mainly depend upon the fiber content, length of individual fibers, orientation, and fiber to matrix bonding and lastly, the arrangement of both the fibers. The main advantages of these composites are reduced cost by one fiber/filler. An expensive fiber can be replaced with yet another low cost fiber/filler. The required mechanical and physical properties of the composites are obtained by choosing those reinforcements which contain different properties. This is not possible in the case of individual fiber composites. Many investigations in the hybrid composite with different fibers/fillers have been carried out by researchers (Bolvari et al 1997, Wang et al 2003, Kishore et al 2000)

1.8 WOVEN FABRICS

Woven fabrics are made by using two or more sets of fibers interlaced at right angles to each other. One is called the warp and the other is called the weft direction. Woven fabrics are generally more durable and are produced on looms in a wide variety of weights, weaves and widths. Bi-directional woven fabrics offer good strength in 0-degree and 90-degree directions, and also permit one laminate to be used for faster composite fabrication. They are made from fibers crimped as they pass over and under one another. Several weaves are used in bi-directional fabrics. In a plain weave, each fill yarn or roving alternately crosses over and under each warp fiber, as shown in Figure 1.3. Those fabrics with higher fabric counts provide better shape, sturdiness and durability. Woven fabric reinforced composites are more popular in the field of polymer composites, because of their balanced properties in the fabric plane as well as their ease of handling during fabrication.
1.9 ADVANTAGES OF THE FIBER REINFORCED POLYMER MATRIX COMPOSITES

Some of the advantages of fiber reinforced polymer matrix composites are:

i. Higher strength to weight ratio
ii. Higher stiffness to weight ratio
iii. High Fracture Toughness
iv. Good wear and abrasion resistance
v. Good puncture resistance
vi. Good corrosion and chemical resistance
vii. Ability to adapt properties to meet wide-ranging performance specifications
viii. Shaped to required dimensional tolerances lead to withholding in long service of components
ix. Improved impact, compression, fatigue and electrical properties
x. Enhanced damping capabilities
xi. Low cost
1.10 MANUFACTURING METHODS OF FIBER REINFORCED POLYMER MATRIX COMPOSITES

1.10.1 Hand Lay-Up and Spray Techniques

Hand lay-up and spray techniques are two simple polymer processing techniques. Fibers can be laid onto a mold by hand and the resin (unsaturated polyester, being one of the most common) is sprayed or brushed on. Frequently, resin and fibers (chopped) are sprayed together onto the mold surface. In both cases, the deposited layers are densified with rollers. Accelerators and catalysts are frequently used. Curing may be done at the room temperature or at a moderately high temperature in an oven.

1.10.2 Filament Winding

Filament winding is yet another versatile technique in which continuous tow or roving is passed through a resin impregnation bath and wound over a rotating or stationary mandrel. The winding of roving can be either polar (hoop) or helical. In polar winding, the fiber tows do not cross over, while in the helical they do. The fibers are, of course, laid on the mandrel in a helical fashion in both polar and helical windings; the helix angle depends on the space of the object to be made. Successive layers are laid on at a constant or varying angle until the desired thickness is attained. Curing of the thermosetting resin is done at an elevated temperature and the mandrel is removed. Very large cylindrical (e.g., pipes) and spherical vessels and built by filament winding. Glass, carbon, and aramid fibers are routinely used with epoxy, polyester, and vinyl ester resins to produce filament wound shapes.
1.10.3 Resin Transfer Molding

Resin transfer molding is a closed-mold, low-pressure process. A preform made of the desired fiber (carbon, glass, or aramid) is placed inside a mold. A liquid resin such as epoxy or polyester is injected into the mold by means of a pump. Reinforcements can be stitched, but more commonly, they are made into a preform which retains its shape during the injection of the polymer matrix. The resin is allowed to cure and to form a solid composite. The polymer viscosity should be low enough for the fibers to be come easily wet. Additives to enhance surface finish, flame retardancy, weather resistance, curing speed, etc. may be added to the resin.

Main advantages of this method:

i. Large complex shapes and curvatures can be made easy
ii. The level of automation is higher than in other processes
iii. Layup is simpler than in manual operations
iv. The process takes less time
v. The process involves a closed mold, so styrene emissions can be reduced to a minimum

1.10.4 Pultrusion

In this process, continuous section of polymer matrix composites with fibers oriented mainly axially, are produced. Continuous fiber tows come from various creels. Mat or biaxial fabric may be added to provide certain degree transverse strength. These are passed through a resin bath containing a catalyst. After this, the resin impregnated fibers pass through a series of wipers to remove any excess polymer and then through a collimator before entering the heated die. A thorough collimator wet-out of the rovings is very important. Stripped excess resin is recirculated to the resin bath. The heated
die has the shape of the finished component to be produced. The resin is
cured in the die and the composite is pulled out. At the end of the line, the
part is cut by a flying saw to a fixed length. Typically, the process can
produce continuously at a rate of 10 to 200 cm/min. The exact speed depends
on the type of the resin and the cross-sectional thickness of the part being
produced.

1.10.5 Autoclave-based Methods

Autoclave-based methods or bag molding processes are used to
make large parts. Before looking at this, it is important to understand the term
prepregs. The term prepreg is the abbreviation of preimpregnated fibers.
Prepregs thus represent an intermediate stage in the fabrication of a polymeric
composite component. Prepregs can be made by a number of techniques.
Autoclave-based processing of PMCs results in a very high quality product.
An autoclave is a closed vessel in which processes occur under simultaneous
application of high temperature and pressure. Heat and pressure are applied to
appropriately stacked prepregs. The combined action of heat and pressure
consolidates the laminae, removes the entrapped air, and enables the curing of
polymer matrix. Autoclave processing of composites thus involves a number
of phenomena: chemical reaction, resin flow, and heat transfer. Vacuum or
pressure bags containing fibers in a predetermined orientation in a partially
cured matrix (prepreg) are used in an autoclave for densification and curing of
resin. Chopped fibers mixed with resin can also be used in the place of
prepergs. An autoclave is, generally, a cylindrical oven that can be
pressurized. The bags consist of thin and flexible membranes made of rubber
that separates the fiber layups from the compressing gases during curing of
the resin. Densification and curing are achieved by pressure differentials
across the bag walls. In vacuum moldings, the bag contents are evacuated and
atmospheric pressure consolidates the composites. High fiber volume
fractions (60-65%) can be obtained in autoclave-based processing of PMCs.
1.11 BASIC CONCEPTS OF TRIBOLOGY

1.11.1 Wear

Wear is defined as the progressive damage due to relative contact between adjacent working parts resulting in material loss. When surfaces of the solid slide over one another, they not only experience friction, but also wear. Thus the material is lost from both the surfaces, even in cases where one is much harder than the other. Even though a minimum degree of wear is expected to occur during the normal operation of equipment, excessive friction causes premature wear. This in turn leads to expenditure that occur due to equipment failure, cost for replacement parts and down time (Zhang 1988). Hence wear is also responsible for overall loss in system efficiency. In the Wear phenomenon which occurs under normal mechanical and practical situations, the wear rate changes through three different stages:

**Stage 1:** It is the run in period where surfaces adapt to each other and the wear rate might vary between high and low

**Stage 2:** It is the mid-age process, where a steady rate of aging is in motion. The operational life of most components is decided at this stage.

**Stage 3:** It is old-age period; the components are subject to rapid failure due to high rate of aging.

Wear is generated in the metal by the plastic deformation of the surface and detachment of particles in the form of wear debris. Wear can occur by the contact of one metal surface with other metal surface, non metals, flowing liquids or solid particles (Yust 1985, Friedrich et al 2002). In the field of composite materials till date the knowledge on tribological behavior has not been studied much, only limited works have been were carried out with the some degree of envisaged capability. Thus more and
more researchers are focusing on the tribological study of composite materials.

Friction is a force that resists relative motion between two surfaces in contact. This frictional force could be a desirable or an undesirable one depending upon the application. In certain applications such as tire traction on pavement and braking, cylinder liners, gears, rely on the beneficial effects of friction for their effectiveness. On the other hand, in some applications such as operation of engines and parts, bearings and gears, friction is undesirable because it causes wear and produces heat, which frequently leads to impulsive failure. The coefficient of friction of polymers always exhibits a lower value, ie, in between the 0.1 to 0.5 when compared to the ceramic and metals, either when they are self mated or when they slide against other materials. Hence polymers were used without lubrication in the field of tribological applications. Generally, the polymer component slides against the harder counter surfaces. The polymer is much more amenable than other metals or ceramics, with values of elastic modulus typically less than the metals. The strength of the polymer is much lesser and thus, it is also reasonable to consider ceramic or metallic counterfaces when sliding against the polymers to act as rigid bodies. The wear phenomenon classified according to the types of contact and applications of the components are as follows:

i. Adhesive wear

ii. Abrasive wear

iii. Fatigue

iv. Erosion

v. Corrosion

The polymeric matrix composites were mainly subject to dry sliding and abrasive wear in various applications.
1.11.1.1 Adhesive wear

When two surfaces slide relative to one another, there is a tendency for one material to transfer onto the counterface. At the interface, asperities come with contact and bonding takes place due to adhesion. Thus, adhesive wear may result from adhesion between the polymer and counterface, which is smooth. This causes deformation only in the surface layers of the polymers. If the counterface is rough, the asperities will cause a significant degree of deformation in the polymer. Also, the abrasion related with plastic deformation of the polymer or fatigue growth in the deformed region leads to wear of the polymer (Palabiyik and Bahadur 2002, Rymuza 2007). Thus, the adhesive wear occurs because of two separate mechanisms between the surfaces:

1. Relative motion between the two surfaces by direct contact and plastic deformation creates wear debris and material transfer from one surface to another.

2. Unified adhesive forces hold two surfaces together although they are separated by a measurable distance with or without any actual transfer of material.

![Diagram of Adhesive Wear](image)

**Figure 1.4** Adhesive wear-contact areas of the two sliding surfaces
When two surfaces slide on each other, the adhesive junctions and their type and strength play an important role in the mating surfaces (Archard 1953), as shown in Figure 1.4. These contact points represent the real area of contact. The adhesion component stems from the adhesive junctions formed on the spots of real contact between the mated surfaces.

1.11.1.2 Abrasive wear

Abrasive wear is defined as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface. Plastic flow and the brittle fracture are their primary reasons of the abrasive wear. Thus, abrasive wear is caused by hard asperities on the counterface and or hard particles that move over polymer surface. This is evident in the agriculture, mining, mineral processing, earth moving industries and dirt, rock solids and slurries show the effect of abrasion. Abrasive wear is classified into two types (Misra and Finnie 1980, Hutchings 1992) namely

(i) Two body abrasion and

(ii) Three body abrasion

In both the above types, the soft surface is ploughed by a relatively hard material. In the two body abrasion, a hard rough body plough in to a softer body. Examples of two body abrasion (Figure 1.5(a)) is pipe and chute liners used to transport abrasive materials, blades and components in agricultural and earth moving machinery, grinding, cutting and machining process.
In the three body abrasion (Figure 1.5(b)), a third body such as a hard granular sand introduced in between the sliding abrasive surfaces causes one or both of them undergo abrasive wear get crushed and cut grooves. Simple examples for the abrasive wear are sleeve bearing and bushes operating in abrasive environment, vehicle spring bushes, chain wear strips and rope sleeve bearings. The three main mechanisms of abrasive wear are i) plowing, ii) cutting and iii) fragmentation.

Plowing occurs when the material is displaced to a side, away from the wear particles, resulting in the formation of grooves that do not cause direct removal of material. The displaced material forms ridges adjacent to the grooves, which could be removed by passing abrasive particles. Cutting occurs when the material is separated from its surface in the form of primary debris, or microchips, with a little or no material displaced to the sides of the
grooves. This mechanism closely resembles conventional machining. Fragmentation occurs when the material is separated from a surface by a cutting process and the indenting abrasive causes localized fracture of the wear material. These cracks then freely propagate locally around the wear groove, resulting in additional material removal spalling.

1.11.1.3 Fatigue wear

Fatigue wear is a process by which the surface of a material is weakened by cyclic loading, and is produced when the wear particles are detached by cyclic growth of micro cracks on the surface. These micro cracks are either superficial cracks or subsurface cracks.

1.11.1.4 Erosive wear

Erosive wear is caused by the impact of particles of solid or liquid against the surface of an object. The impacting particles gradually remove material from the surface through repeated deformations and cutting actions. An example is the erosive wear associated with the movement of slurries through piping and pumping equipment.

1.11.1.5 Corrosive wear

Corrosive wear is defined as the degradation of materials in which both corrosion and wear mechanisms are involved. In corrosion, there is corrosive (oxidation) attack on the surfaces. The sliding action then wears off the corroded surface film.
1.11.2  Factors Affecting the Wear

In industries and domestic applications, wear is the key factor which creates problems in the parts which were subjected to the sliding or rolling contact. Wear causes the failure of the system, resulting in the replacement of the worn component. Wear phenomenon, affecting the overall operating efficiency of the engineering system, consumes more lubricants. Therefore the frequency of replacements of parts is also higher. The main factors manipulating wear rate (Bhushan and Gupta 1991) are given below

i. Design criteria: type of motion, transmission of load, level of lubrication, thermal and environmental causes.

ii. Operating conditions: speed (velocity), area of contact, contact pressure and surface condition

iii. Abrasive characteristics: hardness, size and shape

iv. Material properties: composition, hardness, microstructure, work hardening ability and resistance to corrosion.

The fiber reinforced polymer composites should have low friction and better wear performance. Some of the applications of fiber reinforced composites are bearings, bushes, seals, gears, chute liners, the components used for mining, material handling and agricultural machineries. The two categories of parameters that control the wear parameters are:

i. The parameters exterior to the material subject to surface interaction i.e., external load normal to the contact surfaces, sliding velocity, sliding distance (transient and steady state
period), fiber orientation, environment and temperature, surface finish and the counterpart

ii. The parameters interior to the material subject to surface interaction i.e., reinforcement of fiber/filler type, matrix material, filler size and its circulation, reinforcement fiber/filler shape, microstructure of the matrix and volume fraction of the reinforcement/filler and matrix.

The selection of polymer matrix composite materials may be based on the end use. Fiber reinforced composites employed for tribological applications prove to be superior materials by its own elevated properties resulting in lower coefficient of friction, low wear rate, better lubrication and stability at higher loads and temperatures (Friedrich 1986).

1.12 CHAPTER SCHEMATA

The research work implemented in this thesis, on the basis of experimental work conducted and results evaluated are presented in seven chapters. Chapter 1 introduces basics of composites materials and their behavior under tribological conditions which includes wear and friction. Chapter 2, the literature survey behind the work, includes reviewed work on mechanical and thermo-mechanical, and tribological behaviors of polymer matrix composites both with and without the addition of the filler materials. This chapter also includes the objectives of the present research work. Chapter 3 discusses the methods used for fabrication of PMCs, the techniques and experimental setups used to conduct the mechanical and tribological investigation of PMCs both with and without ceramic filler. Chapter 4 highlights the mechanical behavior of ceramic particles filled and unfilled
PMCs, such as hardness, tensile strength, tensile modulus and flexural strength. Also, this chapter illustrates the thermo-mechanical behavior of ceramic particles filled and unfilled PMCs through dynamic mechanical analysis. Chapter 5 deals with the role of ceramic particles filled and unfilled PMCs on dry sliding conditions with wear and friction factors. Chapter 6 explains the abrasive behaviors such as two-body and three-body abrasive wear behavior of ceramic particles filled and unfilled PMCs. Finally, in chapter 7, conclusions and suggestions for future work are highlighted.