CHAPTER 1

INTRODUCTION

1.1 TRIBOLOGY

Tribology is a field of science defined in 1967 by a committee of the Organization for Economic Cooperation and Development. ‘Tribology’ is derived from the Greek word ‘tribos’ meaning rubbing or sliding, which focuses on friction, wear and lubrication of interacting surfaces in relative motion.

Wear is the major cause of material wastage and loss of mechanical performance and any reduction in wear can result in considerable savings. Friction is a major cause of wear and energy dissipation. Considerable savings can be made by improved control of friction. It is estimated that one third of the world’s energy resources in present use is needed to overcome friction in one form or another. Lubrication is an effective means of controlling wear and reducing friction.

Tribology is a field of science which applies an operational analysis to problems of great economic significance such as reliability, maintenance and wear of technical equipment ranging from household appliances to spacecraft. The question is why ‘the interacting surfaces in relative motion’, (which essentially means rolling, sliding, normal approach or separation of surfaces), are so important to our economy and why they affect our standard of living. The answer is that surface interaction dictates or controls the functioning of practically every device developed by man. Everything that man makes wears out, almost always as a result of relative motion between surfaces. An analysis of machine break-downs shows that in majority of the cases failures and stoppages
are associated with interacting moving parts such as gears, bearings, couplings, sealings, cams, clutches, etc. (Hutchings 1992).

The commonly used materials for reducing friction and wear are metals and their alloys, ceramics, solid lubricants, polymers and their composites. Among these polymers based composite materials find use in a variety of applications owing to their high strength, lightness, ease of fabrication, and availability of wider choice. One of the areas where their use has been found to be advantageous is the situation involving contact wear. These composite materials are increasingly employed in tribological applications owing to their ever increasing demands in terms of stability at higher loads, temperatures, better lubrication, and wear properties.

1.2 COMPOSITE MATERIALS

Composite materials are engineering materials made from two or more constituent materials that remain separate and distinct on a macroscopic level while forming a single component. There are two categories of constituent materials: matrix and reinforcement. The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions. The reinforcements impart their special mechanical and physical properties to enhance the matrix properties.

The primary functions of the matrix are to transfer stresses between the reinforcing fibers/particles and to protect them from mechanical and/or environmental damage whereas the presence of fibers/particles in a composite improves its mechanical properties such as strength, stiffness etc. The objective is to take advantage of the superior properties of both materials without compromising on the weakness of either. As defined by Agarwal and Broutman (1990), composite means material having two or more distinct constituent materials or phases.
1.3 CLASSIFICATION OF COMPOSITES

1.3.1 Classification based on geometry

Most composite materials developed thus far have been fabricated to improve mechanical properties such as strength, stiffness, toughness, and high temperature performance. It is natural to study together the composites that have a common strengthening mechanism. The strengthening mechanism strongly depends on the geometry of the reinforcement. Therefore, it is quite convenient to classify composite materials on the basis of the geometry of a representative unit of reinforcement. Figure 1.1 represents a commonly accepted classification scheme for composite materials.

1.3.1.1 Fibrous composite

A fiber is characterized by its length being much greater compared to its cross-sectional dimensions. The dimensions of the reinforcement determine its capability of contributing its properties to the composite. Fibers are very effective in improving the fracture resistance of the matrix since a reinforcement having a long dimension discourages the growth of incipient cracks normal to the reinforcement that might otherwise lead to failure, particularly with brittle matrices.

Man-made filaments or fibers of non-polymeric materials exhibit much higher strength along their length since large flaws, which may be present in the bulk material, are minimized because of the small cross-sectional dimensions of the fiber. In the case of polymeric materials, orientation of the molecular structure is responsible for high strength and stiffness.
Figure 1.1  Classification of composite materials

Fibrous composites can be broadly classified as single layer and multi-layer composites on the basis of studying both the theoretical and experimental properties. Single layer composites may actually be made from several distinct layers with each layer having the same orientation and properties and thus the entire laminate may be considered a single layer composite. Most composites used in structural applications are multi-layered; that is, they consist of several layers of fibrous composites. Each layer or lamina is a single layer composite and its orientation is varied according to design. Several identical or different layers are bonded together to form a multi-layered composite usable for engineering applications. When the constituent materials in each layer are the same, they are called simply laminates. Hybrid laminates refer to multi-layered composites consisting of
layers made up of different constituent materials.

Reinforcing fibres in a single layer composite may be short or long compared to its overall dimensions. Composites with long fibers are called continuous fiber reinforced composites and those with short fibers, discontinuous fiber reinforced composites. The continuous fibers in single layer composites may be all aligned in one direction to form a unidirectional composite. Such composites are fabricated by laying the fibers parallel and saturating them with resinous material. The bidirectional reinforcement may be provided in a single layer in mutually perpendicular directions as in a woven fabric. The bidirectional reinforcement may be such that the strengths in two perpendicular directions are approximately equal. The orientation of discontinuous fibers cannot be easily controlled in a composite material. So fibers can be either randomly oriented or preferred oriented. In most cases the fibers are assumed to be randomly oriented in the composites. However, in the injection moulding of a fiber reinforced polymer, considerable orientation can occur in the flow direction which causes preferred oriented fibers in the composites.

1.3.1.2 Particulate Composites

As the name itself indicates, the reinforcement is of particle nature (platelets are also included in this class). It may be spherical, cubic, tetragonal, a platelet, or of other regular or irregular shape, but it is approximately equiaxed. In general, particles are not very effective in improving fracture resistance but they enhance the stiffness of the composite to a limited extent. Particle fillers are widely used to improve the properties of matrix materials such as to modify the thermal and electrical conductivities, improve performance at elevated temperatures, reduce friction, increase wear and abrasion resistance, improve machinability, increase surface hardness and reduce shrinkage. Also, in case of particulate reinforced composites the
particle can be either randomly oriented or preferred oriented.

1.3.2 Classification based on type of matrix material

Composites are classified as:

- Metal Matrix Composites (MMC)
- Ceramic Matrix Composites (CMC)
- Polymer Matrix Composites (PMC)

1.3.2.1 Metal Matrix Composites

Metal Matrix Composites have many advantages over monolithic metals like higher specific modulus, higher specific strength, better properties at elevated temperatures, and lower coefficient of thermal expansion. Because of these attributes metal matrix composites are under consideration for a wide range of applications viz. combustion chamber nozzle (in rocket, space shuttle), housings, tubing, cables, heat exchangers, structural members etc.

1.3.2.2 Ceramic matrix Composites

One of the main objectives in producing ceramic matrix composites is to increase the toughness. It is often found that there is improvement in strength and stiffness of ceramic matrix composites.

1.3.2.3 Polymer matrix composites

Most commonly used matrix materials are polymeric. In general, the mechanical properties of polymers are inadequate for many structural purposes. In particular their strength and stiffness are low compared to metals and ceramics. These difficulties are overcome by reinforcing other materials with polymers. Secondly, the processing of polymer matrix composites need
not involve high pressure and doesn’t require high temperature. Also equipments required for manufacturing polymer matrix composites are simpler. For this reason, polymer matrix composites developed rapidly and soon became popular for structural applications.

Two types of polymer composites are:

- Fiber reinforced polymer (FRP) composites.
- Particle reinforced polymer (PRP) composites.

1.3.2.3.1 Fiber Reinforced Polymer composites

Common fiber reinforced composites are composed of fibers and a matrix. Fibers are the reinforcement and the main source of strength while matrix glues all the fibers together in shape and transfers stresses between the reinforcing fibers. The fibers carry the loads along their longitudinal directions. Sometimes, fillers might be added to smoothen the manufacturing process, impart special properties to the composites, and/or reduce the product cost. Common fiber reinforcing agents include asbestos, carbon / graphite fibers, beryllium, beryllium carbide, beryllium oxide, molybdenum, aluminium oxide, glass fibers, polyamide, natural fibers etc. Similarly, common matrix materials include epoxy, phenolic, polyester, polyurethane, peek, vinyl ester etc. Among these resin materials, epoxy is widely used for its higher adhesion and less shrinkage property.

1.3.2.3.2 Particle Reinforced Polymer composites

Particles used for reinforcing include ceramics and glasses such as small mineral particles, metal particles such as aluminium and amorphous materials, including polymers and carbon black. Particles are used to increase the modules of the matrix and to decrease the ductility of the matrix. Particles are also used to reduce the cost of the composites. Reinforcements and matrices can be common, inexpensive materials and are easily processed. Some of the useful properties of ceramics and glasses include high melting
temperature, low density, high strength, stiffness, wear resistance, and corrosion resistance. Many ceramics are good electrical and thermal insulators. Some ceramics have special properties; some ceramics are magnetic materials; some are piezoelectric materials; and a few special ceramics are even superconductors at very low temperatures. Ceramics and glasses have one major drawback: they are brittle. An example of particle reinforced composites is an automobile tyre, which has carbon black particles in a matrix of poly-isobutylene elastomeric polymer.

1.4 POLYMER

Polymers are large class of materials consisting of many molecules that can be linked together to form long chains by covalent bonds, thus they are known as macromolecules. They have extraordinary properties, so they can play an essential role in everyday life. (Seymour 1978).

Engineering polymers are of the thermoplastic and thermosetting type. A thermoplastic is one, which dissolves in selected solvents and which may be heated and cooled, reversibly, without decomposition. Few of the well-known thermoplastics used in composites are polyamide (PA), polycarbonate (PC), polyethylene (PE), polyvinyl chloride (PVC) and polystyrene (PS).

Unlike thermoplastics, thermosetting polymers do not dissolve in solvents and do not get softened on heating. Thermosetting resins are usually low viscosity liquids or low molecular weight solids that are formulated with suitable additives known as cross-linking agents to induce curing and with filler or fibrous reinforcements to enhance properties as well as thermal and dimensional stability. Thermosetting polymers become permanently hard when heat is applied and do not soften upon subsequent heating. During the initial heating, covalent cross-links are formed between adjacent molecular
chains.

The thermoset include vinyl esters, polyesters, phenol and epoxy resins. Some of the thermoplastics and thermoset with their characteristics and applications are listed in Table 1.1 (Edwards 1998). Limited water resistance, working temperature range and shrinkage associated with polyesters and phenolic resins have made the epoxies to stand out, despite being a little on the higher side when viewed from cost considerations.

Epoxies offer excellent water resistance, higher working temperatures and very low shrinkage coupled with easy processability. Finally a third category of polymers may be mentioned here, which display rubber like elasticity called ‘elastomers’. Natural rubber (NR), acrylonitrile butadiene rubber (ANBR) and styrene butadiene rubber (SBR) are to be mentioned in this class. These are used in specific applications where large deformations are required or where toughening with fillers in some of the polymers are called for. Phenolic resins (like the popular one and commercially known as Bakelite) find wider applications, especially in non-engineering day-to-day applications involving the plastic material. These can be compounded with a large number of fillers or resins to form blends for improved properties.
### Table 1.1 Characteristics and uses of a few polymeric materials

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Properties</th>
<th>Main Uses</th>
<th>Example Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy resin</td>
<td>Good electrical insulator, hard, brittle unless reinforced, resists chemicals well.</td>
<td>Casting and adhesives, bonding of other materials. Used for printed circuit boards (PCB’s) and surface coatings.</td>
<td><img src="image" alt="Epoxy Resin" /></td>
</tr>
<tr>
<td>Melamine formaldehyde</td>
<td>Stiff, hard, strong, resists some chemicals and stains.</td>
<td>Laminates for worksurfaces, electrical insulation, tableware.</td>
<td><img src="image" alt="Melamine Formaldehyde" /></td>
</tr>
<tr>
<td>Polyesters Resin</td>
<td>Stiff, hard, brittle unless laminated, good electrical insulator resists chemicals well.</td>
<td>Casting and encapsulation, bonding of other materials, car bodies, boats.</td>
<td><img src="image" alt="Polyesters Resin" /></td>
</tr>
<tr>
<td>Vinyl esters</td>
<td>Rigid, translucent, good corrosion resistance, low viscosity</td>
<td>Chemical tanks, ducts, piping, process equipment.</td>
<td><img src="image" alt="Vinyl Esters" /></td>
</tr>
<tr>
<td>Thermoplastic polymers</td>
<td>Rigid, clear, tough, good creep and fatigue resistance, wide range temperature resistance (~40 to 200 °C)</td>
<td>Carbonated drink bottles, business machine parts, synthetic fibers, parts for TV tuners and transformers, fire alarm parts, coffee makers and toasters</td>
<td></td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Polyesters (thermoplastic)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nylons</td>
<td>Rigid, translucent, tough, hard wearing, fatigue and creep resistant, resistant to fuels, oils, fats and most solvents, steam sterilizable</td>
<td>Gear wheels, bushings, zips, pressure tubing, synthetic fibers, bearings partially for food processing machinery, carburettor parts</td>
<td></td>
</tr>
<tr>
<td>Polyethylene (low density)</td>
<td>Flexible, translucent weather proof, easy to process by most methods, low cost, excellent chemical resistance</td>
<td>Squeeze bottles, toys, utility kitchen ware, high frequency insulation, garment bags, and chemical tank linings.</td>
<td></td>
</tr>
<tr>
<td>Polyurethane (thermoplastic)</td>
<td>Flexible, clear, elastic, wear resistant, impermeable</td>
<td>Soles and heels for sport shoes, football boots, hammer heads, seals, gaskets.</td>
<td></td>
</tr>
</tbody>
</table>
1.4.1 Thermo plastics

Thermoplastics can be heated and shaped many times. Thermoplastics will soften when they are heated and can be shaped when hot. The plastic will harden when cooled, but can be reshaped because there are no links between the polymer chains which is clearly shown in Figure 1.2. Some common thermoplastics are ABS (acrylonitrile butadiene styrene), Nylon (polyamide), acrylic (polymethyl methacrylate), PVC (polyvinyl chloride), polystyrene, polypropylene and cellulose acetate.

![Image of thermoplastics showing no link between polymer chains](image1.png)

Figure 1.2 Thermoplastics

1.4.2 Thermosetting plastics

Thermosetting plastics can only be heated and shaped once. If re-heated they cannot soften as polymer chains are interlinked. Separate polymers are joined in order to form a huge polymer which is clearly shown in Figure 1.3. The main thermosetting plastics are epoxy resin, melamine formaldehyde, polyester resin and urea formaldehyde.

![Image of thermosetting plastics showing links between polymer chains](image2.png)

Figure 1.3 Thermosetting plastics
1.4.3 Epoxies

Epoxies are defined as a molecule containing more than one epoxide groups. The epoxide group also termed as, oxirane or ethoxyline group, is shown below.

\[
R-OCH-\text{CE}_2
\]

**Figure 1.4 (a) Epoxide group**

These resins are thermosetting polymers and are used as adhesives, high performance coatings and potting and encapsulating materials. These resins have excellent electrical properties, low shrinkage, good adhesion to many metals and resistance to moisture, thermal and mechanical shock. Viscosity, epoxide equivalent weight and molecular weight are the important properties of epoxy resins.

Another attribute, which has placed epoxies above others, is the easy processability with the addition of a curing agent and with or without application of heat (Lee and Neville 1967). Epoxy prepolymer contain epoxide end groups (Figure 1.4 (a)) and pendant hydroxyl groups as the repeating units in the chain. Hence, these can be cured or hardened by addition of polyamines, which react with epoxide groups at room temperature, or by the addition of cyclic anhydrides, which react with hydroxyl pendant groups at elevated temperatures. Most of the epoxies are prepared by the reaction of epichlorohydrin and bisphenol-A. Owing to the presence of pendant hydroxyl groups, epoxies bond well with the other materials. The uncured epoxy resins have a variety of physical forms ranging from low to high viscosity liquids and can be used with a range of curing agents. These offer the fabricator a wide range of processing conditions to choose from based on the resources at his disposal and the requirements expected of the cast products. A common version of epoxy based groups used in engineering applications is the
diglycidyl ether of bisphenol-A (DGEBA) that contains two epoxide groups one at each end of the molecule as shown in the chemical representation cited in Figure 1.4 (b).

![Structure of DGEBA](image)

**Figure 1.4 (b) Structure of DGEBA**

One of the great advantages of epoxies is the wide variety of cure conditions that can be used to achieve a good cure. This variety of conditions arises because epoxies cure by the reaction of two materials - resin and hardener (curing agent) resulting in a wide variety of properties. Polyesters, too, have a wide variety of resin choices available, but the curing agent is almost always limited to peroxide catalyst with styrene. Therefore, in considering epoxy curing conditions and comparing them to polyester cure conditions, both the type of resin and the curing system need to be considered with epoxies.

### 1.5 REINFORCEMENTS

The principal purpose of the reinforcement is to provide superior levels of strength and stiffness to the composite. In a continuous fiber-reinforced composite, the fibers provide all the strength.

#### 1.5.1 Fibers

Fibers are another important variety of reinforcing agents. They have good strength and directional property. Carbon, glass and Kevlar are the most important fibrous materials used for making composites. Among these, the glass fibers are quite popular and are available in different types, depending on their
composition like E-glass, C-glass, and S-glass. Fibers are also used as unidirectional woven clothes. As mentioned in section 1.1, nowadays, natural fibers are also used in remarkable quantities to make successful composite products. Table 1.2 represents the details of the fibers used in PMCs.

**Table 1.2  Details of fibers and their typical properties used in PMCs**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E-glass</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.54</td>
</tr>
<tr>
<td>Tensile strength (GPa)</td>
<td>3.45</td>
</tr>
<tr>
<td>Specific strength (GPa)</td>
<td>1.34</td>
</tr>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>72.5</td>
</tr>
<tr>
<td>Specific modulus (GPa)</td>
<td>28.1</td>
</tr>
<tr>
<td>Elongation at fracture (%)</td>
<td>4.5</td>
</tr>
</tbody>
</table>

**1.5.1.1  Glass fibers**

Both continuous and discontinuous glass fiber reinforced composites have found extensive application, ranging from nonstructural, low performance uses such as panels in aircraft and appliances, to such high performance applications as rocket motor cases and pressure vessels. The reasons for the widespread use of glass fibers in composites, both in the past and in the present, include competitive price, availability, ease of handling and processing, high strength and other acceptable properties. E-glass fibers are produced using calcium aluminoborosilicate formulation that produces beneficial mechanical properties at a very reasonable cost.

**1.5.1.2  Carbon fibers**

Carbon or graphite fibers are the best known and most widely used
reinforcing fibers in advanced composites. Although there are many reasons for this situation, two factors predominate. Firstly, the manufacturing technology for carbon fibers, although complex, is more amenable to large-scale production than those of many of the other advanced fibers. Secondly, carbon fibers have very useful engineering properties which can be readily translated into usable physical and mechanical properties.

1.5.1.3 Aramid fibers

Aramid is a generic term for a class of aromatic polyamide fibers. These high performance fibers are all variations of poly para-phenylene terephthalamide. Fibers with broad range of properties are available. Kevlar 149, for example, has a tensile modulus of 180 GPa and tensile strength of 3450 MPa. The more commonly used Kevlar 49 has a tensile modulus of 131 GPa and tensile strength of 3620 MPa.

1.5.2 Fillers

Fillers are materials often added to polymers to improve tensile and compressive strength, tribological characteristics (including abrasion) and dimensional and thermal stability. A wide range of fillers are used starting from metallic powders to elastomeric fillers. Oxides such as ZrO2, Al2O3, SiO2, TiO2, CuO, CuS, CuF2, PbS, CaS and boron nitride are some of the commonly used metallic fillers.

Among other inorganic fillers, metallic powders, copper and mild steel have been used (Bahadur et al 1992&2000). Other than particulate form, few other fillers like mica have been used which appear as flakes. Organic fillers, which have caught the attention of composite manufacturers, are mainly elastomers. Many works have reported using hydroxyl terminated butadiene rubber (HTBN), amine terminated butadiene rubber (ATBN) and carboxyl terminated butadiene rubber (CTBN).
1.6  PROCESSING OF POLYMER MATRIX COMPOSITES

Most widely used manufacturing methods for laminated fibre composites are Open mold process, Closed mold process and Continuous process.

1.6.1  Open Mold Process

The following processes are open mold process in which mold are not closed during manufacturing process

- Spray lay-up
- Hand lay-up
- Filament winding.

1.6.1.1  Spray Lay-up

In a spray lay-up method, the fibre is chopped in a hand held gun and fed into a spray of catalyzed liquid resin directed at the mold (Figure 1.5). The sprayed, catalyzed liquid resin will wet the reinforcement fibres, which are simultaneously chopped in the same spray gun. The deposited materials are left to cure under standard atmospheric conditions.

Figure 1.5  A typical spray lay-up method
1.6.1.2 Wet Lay-up/Hand Lay-up

The hand lay-up is one of the oldest and most commonly used methods for manufacture of composite parts.

![Diagram showing a typical hand lay-up method](image)

**Figure 1.6 A typical hand lay-up method**

Hand lay-up composites are a case of continuous fibre reinforced composites. Layers of unidirectional or woven composites are combined to result in a material exhibiting desirable properties in one or more directions. Each layer is oriented to achieve the maximum utilization of its properties. Layers of different materials (different fibres in different directions) can be combined to further enhance the overall performance of the laminated composite material. Resins are impregnated by hand into fibres, which are in the form of woven, knitted, stitched or bonded fabrics. This is usually accomplished by rollers or brushes, with an increasing use of nip-roller type impregnators for forcing resin into the fabrics by means of rotating rollers and a bath of resin. Laminates are left to cure under standard atmospheric conditions. A typical hand lay-up method is shown in Figure 1.6.
1.6.1.3 Filament Winding

Filament winding is automated processes for creating parts of simple geometry wherein continuous resin impregnated fibres are wound over a rotating male tool called mandrel. Figure 1.7 depicts a filament winding process where a continuous fibre roving passes through a shuttle, which rotates and the roving is wrapped around a revolving or stationary mandrel.

![Figure 1.7 A typical filament winding method](image)

Two basic types of filament winding are (i) the polar or planer method, and (ii) the high helical pattern winding.

1.6.2 Closed Mold Process

The molds are closed and part is confined into the mold cavity in closed mold process. Compression molding and Resin Transfer Molding are the types of closed mold process.

1.6.2.1 Compression molding

Compression molding is one of the oldest manufacturing techniques in
the composites industry. The recent development of high strength, fast cure, sheet molding compounds bulk molding compounds and advancement in press technology is making the compression molding process very popular for mass production of composite parts. Fully formed parts are molded in matched metal compression molds that give the final part shape. In comparison with the injection molding process, better physical and mechanical properties can be obtained in compression molding. Figure 1.8 shows a typical compression mold.

![Figure 1.8 A typical compression mold.](image)

**1.6.2.2 Resin Transfer Molding (RTM)**

This is a low-pressure, closed mould semi-mechanized process. The fibre reinforcement, which may be pre-shaped, is placed in the required arrangement in the cavity of a closed mould and a liquid resin of low viscosity is injected under pressure into the cavity, which is subsequently cured. The main potential advantages of RTM can be summarized as the capability of rapid manufacture of large, complex, high-performance structures with good surface finish on both sides. It also permits the use of foam and other removable cores to yield three-dimensional parts and hollow components as well. Resin transfer molding is a closed mold low pressure process that allows the fabrication of composites ranging in complexity from simple, low performance to complex,
high performance parts and in size from small to large (Figure 1.9).

![Figure 1.9  A typical resin transfer molding.](image)

The process is differentiated from other molding processes in that the dry reinforcement and the resin are combined within the mold to form the composite component. The fibre reinforcement, which may be pre-shaped, is placed into a tool cavity, which is then closed. A tube connects the closed tool cavity with a supply of liquid resin, which is pumped or transferred into the tool to impregnate the reinforcement for subsequent curing. Injection pressure is normally less than 690KPa (100 psi). The displaced air is allowed to escape through vents to avoid dry spots. Cure cycle is dependent on part thickness, type of resin system and the temperature of the mold and resin system. The part cures in the mold, normally heated by controllers.

1.6.3 Continuous Process

Continuous process is the process where the part of constant cross section is produced continuously. The parts may be cut into suitable length at the end of process.
1.6.3.1 Pultrusion

Pultrusion is an automated process used to create shapes by pulling rovings through a shaped and heated die. The use of pultruded parts in aircraft is limited to specialized applications. Practical applications are limited to constant cross-section parts. Pultrusion is used to manufacture constant cross-section shapes, viz., I-beam, box and channels. The Pultrusion process machine consists of six different parts namely, the creel, the resin bath, the forming die, the heated curing die, the pullers and the cut-off saw. The creel is the beginning of the Pultrusion process and is the material storage system from which the fibres and mat or fabric are drawn in the correct sequence to match the design requirements of the structural shape. Virtually all Pultrusion processes utilize a resin impregnation bath to facilitate the impregnation of the resin into the fibre structure. The use of pre-impregnated fibres eliminates the resin bath.

Two types of dies are used in Pultrusion process, namely, the forming and the heating or curing die. Forming is done immediately after the impregnation process. Forming dies are normally attached to the heating or curing die in order to provide the correct relationship between the forming and the heated curing step. The rovings go through a heated die that represents the cross-section of finished part. Curing is accomplished by heating the die. The product is continuously pulled out and as it comes out of the puller mechanism, it is cut to the desired length by an automatic saw. The process is continuous and can be used to manufacture extremely long sections. A typical continuous Pultrusion process is shown in Figure 1.10.
1.7 HYBRID COMPOSITES

Hybrid composites are those composites which have a combination of two or more reinforcement fibres. Hybrid composite materials have extensive engineering application where strength to weight ratio, low cost and ease of fabrication are required. Hybrid composites provide combination of properties such as tensile modulus, compressive strength and impact strength which cannot be realized in composite materials. In recent times hybrid composites have been established as highly efficient, high performance structural materials and their use is increasing rapidly. Hybrid composites are usually used when a combination of properties of different types of fibres have to be achieved, or when longitudinal as well as lateral mechanical performances are required. While considering hybrid composites, one can easily find that, there are a few key advantages a material scientist can get. Cost is one factor, where one can replace the high cost fiber or metal oxides with low cost filler or fiber. Secondly, one can think of the possibility of broadening the mechanical and physical properties of the composites by choosing reinforcements differing in properties. Lastly, the possibility of getting a unique property which is not possible in case of single filler included composites. Most works on hybrid composite using thermoplastic matrix involve fiber (Srivastava and Pathak 1996, Bolvari et al 1996 & Friedrich et al 2002) as one of the constituent reinforcement material. Reports on work using different particulate fillers are also available (Wang et al 2003). Some studies have been done to investigate the
influence of volume fraction of reinforcements and fillers on the mechanical properties.

1.8 ADVANTAGES OF THE FIBER REINFORCED POLYMER MATRIX COMPOSITES

The advantages exhibited by composite materials, which are of significant use in industries are as follows:

- High resistance to fatigue and corrosion degradation.
- High ‘strength or stiffness to weight’ ratio. As enumerated above, weight savings are significant, ranging from 25-45% of the weight of conventional metallic designs.
- Directional tailoring capabilities to meet the design requirements. The fibre pattern can be laid in a manner that will tailor the structure to efficiently sustain the applied loads.
- Composites offer improved torsional stiffness.

1.9 BASIC CONCEPTS OF TRIBOLOGY

1.9.1 Wear

Wear is a process of removal of material from one or both of two solid surfaces in solid state contact, occurring when two solid surfaces are in sliding or rolling motion together according to Bhushan&Wilcock (1982). Wear of metal occurs by the plastic deformation of the surface and by detachment of particles, which form wear debris. In metals, this process may occur by contact with other metals, non-metallic solids, flowing liquids or solid particles or liquid droplets entrained in the flow of gases (Yust 1985). The rate of removal is generally slow, but steady and continuous. Figure 1.11 shows the five main categories of wear and the specific wear mechanisms that occur in each category.
Figure 1.11 The five main categories of wear and the specific wear mechanisms that occur in each category

Each specific mode of wear looks different to the next, and may be distinguished easily. Till date, much of the knowledge on tribological behaviour of composite materials is empirical, and limited predictive capability exists. Nevertheless, attempts have been made to generalize the tribological behaviour of composite materials and to understand the contribution of interdisciplinary sciences to tribological behaviour (Rohatgi et al. 1990).

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 the polymer always exhibits lower value ie, between 0.1 to 0.5 than the ceramics and metals whether self mated or sliding against other materials. So the polymers are used in the field of tribological applications without lubrication when generally the polymer component is sliding against the harder counter surfaces. The polymer is much more amenable than the metals or ceramics, with values of elastic modulus typically less than the metals. The strength of the polymer is lesser and also reasonable to consider
1.9.2 Classification of wear

Wear processes can be classified into different types according to the type of tribological load and the materials involved, e.g., sliding wear, fretting wear, abrasive wear, and material cavitation.

![Diagram of basic wear mechanisms viewed microscopically]

**Figure 1.12 Basic wear mechanisms viewed microscopically**

Figure 1.12 presents a chart of the effective wear mechanisms. The wear mechanisms can occur individually, successively or concomitantly. Surface fatigue manifests itself through cracking, crack growth, and detachment of wear particles, brought about by alternating loads in near-surface zones of the base body and counter body.

In *abrasion* microcuttings, fatigue due to repeated ploughing, and fracture of the base body caused by the counterbody's hard asperities or by hard particles in the interfacial medium lead to wear.

In *adhesion*, after possibly extant protective surface layers have been broken through, atomic bonds (microwelds) form above all on the plastically deformed microcontacts between the base body and counterbody. If the strength...
of the adhesive bonds is greater than that of the softer friction partner, material eventually detaches from the deformed surface of the softer friction partner and is transferred to the harder one. The transferred material can either remain on the harder friction partner or detach, or even return.

In *tribochemical reactions*, friction-induced activation of loaded near-surface zones causes elements of the base body and/or counter body to react chemically with elements of the lubricant or ambient medium. Compared to the base body and counter body, the reaction products exhibit changed properties and, after reaching a certain thickness, can be subject to brittle may occur.

Nearly all the deformation due to contact or sliding takes place within the polymer, and the surface finish of the hard counterface has a strong influence on the mechanism of the resulting wear. As the emphasis in the present work is laid on dry slide wear and abrasive wear phenomena of polymer composites, the adhesive and abrasive wear aspects is described briefly in the section to follow.

### 1.9.2.1 Adhesive Wear

Adhesive wear is defined as the process occurring due to sliding or rolling contact between two solid surfaces leading to material transfer between the two surfaces or loss from either surface. Wear may result from adhesion between the polymer and counterface which is smooth and involve deformation only in the surface layers of the polymer. On the other hand, if the counterface is rough, then its asperities will cause deformation in the polymer to a significant depth, wear then results either from abrasion associated with plastic deformation of the polymer, or from fatigue growth in the deformed region. When two surfaces slide on one another, their topographic features allow only the contact of asperity peaks as shown in Figure 1.13. These contact points or ‘junctures’ represent the real area of contact. The wear due to the contact of two surfaces follow an equation by Archard (Equation 1.1) on an asperity contact model:
\[ V = k \frac{SL}{3H} \] \hspace{1cm} \ldots (1.1)

where:

- \( V \) - wear volume,
- \( S \) - sliding distance,
- \( L \) - normal load,
- \( H \) - indentation hardness value of softer of wear pair and
- \( k \) - constant which effectively is required to make the formula fit really within an order of magnitude.

This equation represents a steady state wear. However, for all practical purposes, three regions of wear can be identified as shown in Figure 1.13.

![Schematic diagram of asperity junction growth underfrictional force](image)

**Figure 1.13**  Schematic diagram of asperity junction growth underfrictional force

### 1.9.2.2 Abrasive Wear

Abrasive wear occurs whenever a solid object is loaded against particles of a material that have equal or greater hardness. A common example of this problem is the wear of shovels on earth-moving machinery. The extent of
abrasive wear is far greater than may be realized. Any material, even if the bulk of it is very soft, may cause abrasive wear if hard particles are present. For example, an organic material, such as sugar cane, is associated with abrasive wear of cane cutters and shredders because of the small fraction of silica present in the plant fibers.

1.9.2.2.1 Mechanisms of Abrasive Wear

It was originally thought that abrasive wear by grits or hard asperities closely resembled cutting by a series of machine tools or a file. However, microscopic examination has revealed that the cutting process is only approximated by the sharpest of grits and many other more indirect mechanisms are involved. The particles or grits may remove material by microcutting, microfracture, pull-out of individual grains or accelerated fatigue by repeated deformations as illustrated in Figure 1.14. (Pooley et al 1972)

![Diagram of abrasive wear mechanisms](image)

Figure 1.14 Mechanisms of abrasive wear: microcutting, fracture, fatigue and grain pull-out
The first mechanism illustrated in Figure 1.14a, cutting, represents the classic model where a sharp grit or hard asperity cuts the softer surface. The material which is cut is removed as wear debris. When the abraded material is brittle, e.g. ceramic, fracture of the worn surface may occur (Figure 1.14b). In this instance wear debris is the result of crack convergence.

When a ductile material is abraded by a blunt grit then cutting is unlikely and the worn surface is repeatedly deformed (Figure 1.14c). In this case wear debris is the result of metal fatigue. The last mechanism illustrated (Figure 1.14d) represents grain detachment or grain pull-out. This mechanism applies mainly to ceramics where the boundary between grains is relatively weak. In this mechanism the entire grain is lost as wear debris.

1.9.2.2.2 Modes of Abrasive Wear

The way the grits pass over the worn surface determines the nature of abrasive wear. The literature denotes two basic modes of abrasive wear:

- Two-body abrasive wear
- Three-body abrasive wear

Two-body abrasive wear is exemplified by the action of sand paper on a surface. Hard asperities or rigidly held grits pass over the surface like a cutting tool. In three-body abrasive wear the grits are free to roll as well as slide over the surface, since they are not held rigidly. The two and three-body modes of abrasive wear are illustrated schematically in Figure 1.15.
Until recently these two modes of abrasive wear were thought to be very similar, however, some significant differences between them have been revealed. It was found that three-body abrasive wear is ten times slower than two-body wear since it has to compete with other mechanisms such as adhesive wear. Properties such as hardness of the “backing wheel”, which forces the grits onto a particular surface, were found to be important for three-body but not for two-body abrasive wear. Two-body abrasive wear corresponds closely to the ‘cutting tool’ model of material removal whereas three-body abrasive wear involves slower mechanisms of material removal, though very little is known about the mechanisms involved. It appears that the worn material is not removed by a series of scratches as is the case with two-body abrasive wear. Instead, the worn
surface displays a random topography suggesting gradual removal of surface layers by the successive contact of grits.

1.10 FACTORS AFFECTING WEAR

Wear resistance does not form a part of the basic material properties such as thermal conductivity, melting point or density. The wear phenomenon is affected by various factors including processing parameters. Some of the key factors influencing the wear rate are given below.

i. Design criteria - Transmission of load, type of motion, degree of lubrication, temperature and environmental factors.

ii. Operating conditions - Speed, contact area, contact pressure and surface condition.

iii. Abrasive characteristics - Hardness, shape, size and their distribution.

iv. Material properties - Composition, hardness, microstructure, work hardening ability and resistance to corrosion.

Wear is one of the most commonly encountered industrial and domestic problems leading to replacement or repair of engineering components. Wear, while rarely being catastrophic, reduces the operating efficiency, increases lubricant consumption and rate of component replacement. Several applications of the FRP composites require low friction and better wear performance, for example, brakes, clutches, gears, seals, bushes, bearings, chute liners and components used in earth moving and agricultural machinery.

The principle tribological parameters that control the friction and wear performance of FRP composites can be classified into two categories:

1) Extrinsic to the material undergoing surface interaction i.e., the load normal to the tribo-contact, the sliding velocity, the sliding distance
(transient and steady state period), the fiber orientation, the environment and temperature, the surface finish and the counterpart.

2) Intrinsic to the material undergoing surface interactions i.e., the reinforcement or filler type, reinforcement or filler size and its distribution, the reinforcement or filler shape, the matrix microstructure and finally the reinforcement or filler volume fraction.

For tribological loaded components, the coefficient of friction, the mechanical load carrying capacity and the wear rate of the materials determine their acceptability for industrial applications. Polymer based composite materials are the ones employed in such applications owing to their ever increasing demand in terms of stability at higher loads, temperatures, better lubrication and wear properties (Lee and Nivelle 1967, Friedrich 1986).

1.11 CHAPTERS SCHEMATA

This thesis prepared on the basis of experimental work contains seven chapters.

Chapter 1 presents a brief introduction to polymer matrix composites, classification of fibers and fillers, processing of polymer matrix composites and wear.

The Chapter 2 highlights the literature review on mechanical, thermo-mechanical and tribological behaviour of fiber and filler reinforced polymer matrix composites. This chapter also includes the aim of the present investigation.

In Chapter 3, the fabrication process, experimental methodology, materials and equipment used for the experimentation and their procedure are explained.
Chapter 4 covers the experimental investigation on mechanical properties, dynamic mechanical analysis of filler and fiber reinforced polymer matrix composites.

Chapter 5 highlights the effect of various tribo-parameters on dry slide wear of filler and fiber reinforced polymer matrix composites.

Chapter 6 describes the abrasive wear behaviour of fiber reinforced polymer matrix composites.

Chapter 7 of the thesis summarizes the specific conclusions drawn from this work and offers suggestion for some future works.