CHAPTER-1

INTRODUCTION

1.1 Introduction

Aluminium alloys are widely used in automobile, aerospace and marine industries due to their low density, good stiffness and reasonably good corrosion resistance, but poor wear resistance of these alloys at ambient and high temperatures limit their use in various tribological applications. Majority of machine components are subjected to sliding wear conditions either at ambient or elevated temperature conditions and fail due to poor wear resistance that causes heavy expenditure in the form of maintenance or replacement of parts. This way, overall situation significantly affects the operating cost of the industries and process plants. Hence, it is important to develop materials which may fulfil the requirement of low cost, light weight, and good wear resistance. Continued efforts have been made to develop materials with different alloying additions and/or dispersion of different hard ceramic particles in the form of carbides, oxides, borides, nitrides etc. [Lee et al., 2002; Ramesh et al., 2011; Sahin, 2003; Wang et al., 2010] in the different aluminium alloy matrices to form composites. Different preparation techniques have also been explored to improve tribological properties. The composite so obtained may have dispersion in the form of fibres or particulates. However, due to isotropic properties particulate aluminium matrix composites (PAMCs) have an edge over fibre reinforced composites. In addition to superior wear resistance, PAMCs also exhibit enhanced mechanical properties such as hardness, specific strength, stiffness and damping capacity as compared to their conventional alloys. PAMCs are becoming potential candidates for manufacturing various automotive components such as brake drums, cylinder blocks, gears, pistons and bearings. All these components undergo wear during their service life. The role of friction is also equally important in these applications. Hence, it is important to have detailed knowledge of wear and friction.

1.2 Wear

Wear may be defined as surface damage or removal of material from one or both of the solid surfaces in contact under sliding, rolling, or impact motion. Generally wear occurs due to interaction of asperities of one surface with another one. During relative motion, these asperities are either deformed or displaced from one surface as wear particles or they may be transferred to the mating surface. Wear is not an inherent material property; rather, it depends on the surface condition and operating parameters [Bhushan, 1999]. Definition of wear is generally based on material loss from one or both of the contacting surfaces. According to the Organization for Economic Co-operation and Development (OECD) research group, wear is defined as the "Progressive loss of substance from the operating surface of a body due to the relative motion", while American Society of Lubrication Engineers (ASLE) defines wear as "removal of material by mechanical action" [Peterson, 1976]. Thus, wear is a surface phenomenon that occurs by displacement and detachment of material. Wear problems generally differ from those involving complete breakage, because wear is generally progressive loss of weight which alters the dimensions of components over a period of time. Wear is undesirable in almost all machine components such as bearings, seals, gears, cams, and pistons, however, it is desirable in cases such as writing with a pencil, machining, polishing, shaving etc. [Bhushan, 1999; Mohan et al., 2015]. Mode of wear may be different i.e. mild or severe depending on materials of contacting parts and their surface conditions. But over a period of time wear affects the ability of the component to function properly and failure of the component may take place in the form of misalignment or breakage of the part.

1.2.1 Types of Wear

Depending on the application and working conditions, components fail with different wear modes such as adhesive, abrasive, surface fatigue, impact wear, corrosive wear, electrical-arc-induced, fretting wear or combination of these. However, adhesion, abrasion or their combination frequently occur in industrial applications. One or more type of wear may be involved during wear process for a particular machine component. Wear is a complex situation in which various wear mechanisms and variables such as structural and operating parameters are involved [Bhushan and Gupta, 1991; Bhushan et al., 1985a, 1985b; Booser, 1984; Bowden and Tabor, 1950, 1964; Burwell,1957/58; Eyre and Scott, 1979; Kragelsky et al., 2013; Lipson, 1967; Sarkar, 2013; Winer and Peterson, 1980]. Structural variables of the components are characterized as contacting materials, lubricants used and their physical, chemical and technological properties, and the operating variables include, load, velocity, distance, humidity and temperature conditions and their functional duration [Blau, 1992]. In addition to this environment effects during wear process are also important. Different types of wear modes are discussed briefly in the following sections.

Adhesive wear occurs due to sliding contact between two nominally flat solid bodies under dry or lubricating conditions. During sliding motion asperities contacts formed at the interface are sheared away which may lead to the detachment of material fragment from one surface and may be attached to another surface. These fragmented particles may get transferred among surfaces in contact several times, or may be removed as loose particles. Several investigators studied various mechanisms involved in transfer of a fragment from the material surface. Archard [1953] suggested that weakest region of the body is generally sheared during sliding and transferred as irregular shape fragments. Another mechanism may involve plastic shearing of successive asperities layers forming wedge shaped fragments [Bhushan, 1999; Kayaba and Kato, 1981; Mohan et al., 2015]. Surface asperities may get plastically deformed or fractured during sliding. Subsurface may also undergo plastic deformation and strain hardened up to some thickness with increased hardness.

Abrasive wear occurs due to the sliding of a hard surface on softer surface. In case of ductile materials the interface is plastically deformed, whereas, for brittle materials it gets fractured during sliding. Abrasive wear can be two-body or three-body. In two-body abrasive wear, hard surface is one of the two rubbing surfaces. In three-body abrasive wear hard surface is a third body which may be small abrasive particles entrapped between two surfaces during sliding. These particles have sufficient hardness and may cause abrasive wear in one or both the mating surfaces. In most of the cases, initial wear mode is adhesive which forms wear particles, and these particles may get entrapped between two contacting surfaces and give rise to three-body abrasive wear [Bhushan, 1999; Bhushan et al., 1985b; Deuis et al., 1996].

Surface fatigue wear occurs due to dynamic loading condition during sliding and rolling. Subsurface or surface cracks are generated when material is subjected to repeated loading and unloading cycles. After a critical number of cycles, materials may fail due to surface damage with the formation of large pits. During fatigue, negligible amount of wear loss occurs before failure. Therefore, amount of weight loss during fatigue is not so important because useful life in terms of number of cycles is more relevant parameter before fatigue failure occurs [Bhushan, 1999; Vingsbo and Hogmark 1981]. During rolling contact fatigue failure time depends on amplitude of repeating shear stress, interface lubrication condition, and fatigue properties of rolling materials [Lundberg and Palmgren 1947]. During sliding contact, cracks are nucleated on the surface or at sub-surface due to deformation which propagate with further loading giving rise to surface fatigue failure.

Impact wear can be classified as erosive and percussive wear. Erosive wear occurs due to the impingement of solid particles, liquid droplets and breaking of bubbles formed in the fluid [ASTM: G 40 – 94, 1994]. Percussive wear occurs due to repeated impact of solid bodies which may lead to the progressive loss of material. Similar to the adhesive and abrasive wear, erosive wear may also cause plastic deformation and/or fracture. Erosion of brittle material takes place due to formation and intersection of cracks which scatter from the point of impact of eroded particle [Finnie, 1960], whereas cutting and deformation (ploughing) mechanisms are responsible for material removal in ductile materials [Bellman and Levy, 1981; Bhushan, 1999; Soderberg et al., 1983]. Cavitation erosion occurs due to implosion of bubbles against solid surface which are formed during the relative motion between fluid and solid [Hammitt, 1980].

Chemical or corrosive wear occurs whensliding, rolling or rotating motion takes place in corrosive media. Corrosion can occur due to chemical or electrochemical interaction between interface and environment. Oxygen is the most corrosive medium in air, hence, chemical wear in air is known as oxidative wear. If the process of sliding is restricted, corrosion process may be slowed down due to the formation of a thin layer on the surface by corrosion products. But, sliding can accelerate corrosion by removal of this layer. Thus, both chemical environment (corrosion) and rubbing are the essential requirements for chemical wear to take place. The common corrosive wear problems occur in various automobile components such as brakes and engines [Bhushan, 1999; Blau, 1992; Stott et al., 1990].

Electrical-arc-induced wear takes place due to the presence of high potential over a thin air film in a sliding process which causes dielectric breakdown and results in arcing. High density arcing over a short period results in melting and re-solidification of heat affected zone. The process of melting and re-solidification may lead to phase change and even hardness may be altered. High density arcs may cause large craters which may be sheared or fractured during sliding or oscillatory motion. These removed fragments may lead to three-body abrasion. Even combination of different modes of wear may take place due to arcing, and finally it may lead to catastrophic failure of the component [Bhushan, and Davis, 1983; Bhushan et al., 1985a; Guile and Juttner, 1980].

Fretting wear may take place when low-amplitude oscillatory motion occurs between two contacting surfaces in tangential direction and the protective film on the surface breaks due to this oscillatory motion. As a result the broken metal oxidises and forms wear debris that causes serious damage to the surface. Fretting is a form of wear, where the normal load causes adhesion among asperities while oscillatory motion causes fracture forming wear debris. Fretting if combined with corrosion is known as fretting corrosion [Barnett, 1955; Hurricks, 1970; Waterhouse, 1992].

1.2.2 Stages of Wear

Wear process is generally expressed in terms of wear rate. Wear rate may be defined as the volume or mass removed per unit time or per unit sliding distance from the surfaces in contact. Wear rate is a complex function of time and does not remain constant. Wear rate may exhibit different patterns such as low in the beginning and high in the later stage or vice versa depending on various situations. The wear rate of materials may depend on counteracting material, surface condition, and operating parameters. Wear process can be distinguished by three different regions in the wear curve (Fig.1.1) and these may be named as: (i) the running-in, (ii) steady- state and (iii) the break down. In running-in period the wear is largely affected by material properties and surface conditions. The running-in period is characterized by a progressive increase in wear loss with sliding distance or operating time. During steady- state period, the wear rate generally remains constant, and during break down period the mass loss may increase exponentially with operating time until failure takes place. A linear nature of wear loss versus operating time may be expected only in abrasive wear situations. Adhesion, surface fatigue and/or tribo-chemical reaction may dominate in the sliding wear that produces the general three period wear patterns [Bhushan, 1999; Blau, 1992; Mohan and Mohan, 2015]

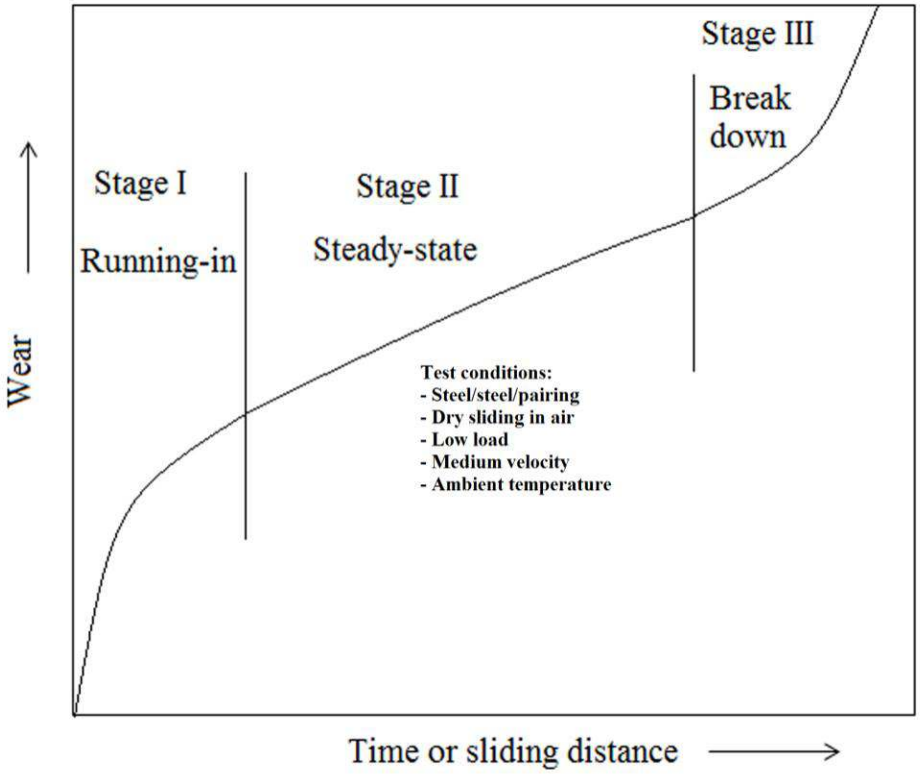

Figure 1.1 - Wear - time curve [Blau, 1992]

1.2.3 Theories of Wear

Different wear mechanisms such as adhesion, abrasion, erosion, and corrosion may be operative during wear process. Different theories which are applicable to wear mechanisms are discussed in subsequent sub-sections.

1.2.3.1 Classical theory

Rabinowicz [1965] while studying wear pattern observed that local plastic deformation of contacting asperities at sufficiently high pressure causes adhesion at contact junctions of mating surfaces. Hardness of the materials in contact plays a major role in deciding the real area of asperity contact; hence, hardness at contact points is of prime importance. But Archard defined wear as a function of sliding speed, normal load and material hardness. However, effect of the material’s microstructure was completely ignored, hence, theory remains limited only to ideal conditions without taking into consideration the nucleation and growth of crack. The material removal was considered only due to cohesive failure of asperities. Archard [1953] developed the following expression for volume loss due to wear,

$$V = \frac{kLW}{H} \tag{1.1}$$

Where, k is wear coefficient, L is sliding distance, W is applied normal load and H is bulk hardness of the material.

Archard concluded that the wear rate was directly proportional to the applied load and assumed average contact area and the wear particles to be constant that makes this equation independent of apparent area of contact. Hence, applied load and hardness remain the governing factors for wear. However, this assumption may not stand true for all conditions, but in most of the material pairs, k ranges from10^{-8} to 10^{-4} for mild wear and 10^{-4} to 10^{-2} for severe wear conditions [Bhushan, 1999; Deuis et al., 1997]

1.2.3.2 Oxidative wear theory

Temperature rise takes place at the contact junctions when materials are in dry sliding contact and causes surface oxidation at interface. The oxide film formed at the interface reduces the shear strength of the interface and wear rate reduces due to the plastic deformation [Quinn, 1983a, 1983b]. The phenomenon in which debris is mostly oxide is called oxidative wear. Toa [1969] observed that the time required to form an oxide film is much larger as compared to breaking of film though it may not be true for all combinations of parameters affecting wear rate. But crack nucleation and its propagation is supposed to be main contributing factor to wear [Batchelor et al.,1986; Srivastava, 2006].

1.2.3.3 Delamination wear theory

Suh [1973] has given delamination wear theory for low sliding velocities with the help of wear debris formed. Adhesive, fretting and fatigue wear can be explained with this theory. This theory can be explained in a sequential manner [Srivastava, 2006; Suh, 1977].

- Adhesion and ploughing are responsible phenomena for load transmission during sliding which may either deform or remove asperities in contact due to repeated loading. This creates relatively smooth surface and a wider area is available for contact for harder asperities during cyclic loading.
- Accumulation of shear plastic deformation takes place with repeated loading due to hard asperities in the soft surface.
- Crack nucleation takes place below surface with subsurface deformation due to highly compressive tri-axial stresses just below the contact regions.
- Propagation of cracks with deformation continues with further loading and the cracks join with neighboring ones. The cracks tend to propagate parallel to the surface at a depth depending on material properties and coefficient of friction.
- Long and thin wear sheets "delaminate" due to these cracks, however, thickness of wear sheet is controlled by the location of subsurface crack growth depending on normal and tangential load.

1.2.3.4 Quinn’s theory

Quinn [1967] proposed wear theory for high sliding velocity conditions. According to his theory, excessive frictional heating at high velocities causes temperature rise and a thick oxide layer is formed on sliding surface. This oxide layer is removed after a critical thickness leading to wear. He further explained that oxide film formed in the beginning is worn away leading to severe wear, but over a period of time worn surface recovers by unknown process and the wear rate decreases drastically. But after a critical thickness the oxide film becomes too weak to withstand the load and frictional shear stress weakens the film and it is removed as debris [Srivastava, 2006].

1.2.3.5 Tribolayer theory

Dry sliding wear mechanism was reviewed by Jiang et al. [1995]. They observed that transition from severe to mild wear after a definite period of sliding time is attributed to formation of stable tribolayer. Tribolayer is formed by transfer of debris from one surface to another. Plastically deformed oxidised debris particles consolidate as hard protective layer that reduces the wear rate. This phenomena is more significant at elevated temperatures and a smooth tribolayer or mechanically mixed layer (MML) is formed which may have particles from both the surfaces. The material may be transferred back and forth many times in the process in order to produce debris. The critical transfer layer thickness changes with sliding conditions, however, debris particles are formed by delamination. Formation of tribolayer has been neglected in both classical adhesive theory and delamination theory of wear. [Deuis et al., 1997; Heilmann et al., 1983]

1.2.4 Types of Wear Debris Particles

Morphology of wear debris particles is important in deciding wear mode both in dry and lubricated conditions. Mild wear is characterised by fine debris particles of 0.01-1µm with relatively smooth worn surface having shallow ploughing grooves, while severe wear is characterised by large particles of 20-200 µm with rough worn surface having deep grooves and cracks. Debris particles can be classified on the basis of their morphology or wear mechanism. It is really difficult to identify the exact wear mechanism, however, it can be classified on the basis of debris particles morphology. Debris particles produced may be in the shape of plate, ribbon, sphere or any irregular shape [Hokkirigawa and Kato, 1988; Rigney, 1992; Ruff et al., 1981; Scott, 1975; Scott and Westcott, 1977].

1.3 Friction

Friction is defined as the resistance to motion during rolling or sliding. It is experienced when one solid body moves tangentially over another contacting body. Friction may be dry friction or fluid friction. Dry friction is also expressed as "Coulomb" friction which occurs between two dry surfaces tending to move relative to each other, while fluid friction exists between adjacent layers in a fluid which move with different velocities relative to each other in a liquid or gaseous lubricants present in between the bearing surfaces. Initial concept of friction was introduced way back in fifteenth and sixteenth centuries by Leonardo da Vinci and Guillaume Amontons. Two basic laws of friction were mentioned as,

- friction is directly proportional to normal load and
- friction does not depend on apparent area of contact.

But later Coulomb clearly distinguished static and kinetic friction and third law stating that friction is independent of sliding velocity was proposed. Friction depends more on system response of contacting materials rather than their properties, however, other factors also contribute such as interface properties and operating conditions. Metals which have clean surfaces without any contamination exhibit high coefficient of friction, whereas, contaminated surfaces have weak adhesion and low coefficient of friction [Bowden and Tabor, 1950, 1964; Buckley, 1981].

1.3.1 Theory of Friction

Several factors which contribute to overall friction are adhesion between mating surfaces, asperities interaction, ploughing of one surface by another one, surface deformation and/or entrapment of wear particles [Bowden and Tabor, 1964; Dowson, 1979; Ludema,1987]. According to Bowden and Tabor [1964] adhesion and deformation are main contributors to friction. They further proposed that interacting asperities plastically deform and attain a pressure equal to hardness (H) of the material. Hence, real area of contact 'A_r' can be calculated as,

$$A_r = \frac{W}{H} \tag{1.2}$$

Assuming that metals weld together over an area of contact and the tangential force (F) required for relative motion is equal to the multiplication of shear strength (S) and real area of contact 'A_r'. Thus, the coefficient of friction (μ) is given by,

$$\mu = \frac{F}{W} = \frac{A_r S}{A_r H} = \frac{S}{H} = \frac{\text{Shear strength of junctions}}{\text{Indentation hardness of softer material}} \tag{1.3}$$

Where W is normal load in Newton and H is flow hardness in N/m^2 and S is shear strength in N/m^2.

Two main factors which contribute to the friction during sliding are adhesion and ploughing as proposed by Bowden and Tabor [1964]. Suh and Sin [1981] introduced a third term called deformation which also contributes to the friction. Suh [1986] proposed that third body wear particle entrapped between two surfaces contribute in a major way to overall friction. Now if we add main contributing factors i.e. (i) adhesion of the flat regions between the sliding surfaces (μ_a), (ii) ploughing by hard asperities and wear particles (μ_{plow}), (iii) deformation of the surface asperities (μ_d) and (iv) entrapment of wear particles (μ_{part}) then the final value will be:

$$\mu = \mu_a + \mu_{plow} + \mu_d + \mu_{part} \tag{1.4}$$

The relative contribution of above mentioned factors depends on the sliding conditions, type of materials and the environment during the wear process [Deuis et al., 1997; Blau, 1992; Suh and Sin, 1981].

1.3.2 Stages of Friction

Friction is caused under same contact conditions that are basic to the wear process, however, they may act differently in different situations. Friction and wear of the metals are largely governed by interaction of asperities of two sliding surfaces. With sliding distance the condition of mating surfaces change which affect the wear and friction properties. Figure 1.2 shows the variation of friction coefficient with time or sliding distance. Friction coefficient has four different stages. During stage I, initially, low value of friction coefficient depends on low loads and shear resistance of contaminants present on the surface, however, it is independent of combination of mating material.

The friction coefficient gradually increases with time due to increased adhesion and asperity interactions resulting due to removal of surface layer. Entrapped wear particles also contribute to increased friction coefficient which attains its maximum value during stage II. In stage III friction coefficient decrease due to formation of protective tribo-chemical surface layer which reduces the ploughing and asperity deformation and finally steady-state condition exists which leads to constant value of friction coefficient in stage IV [Blau, 1992].

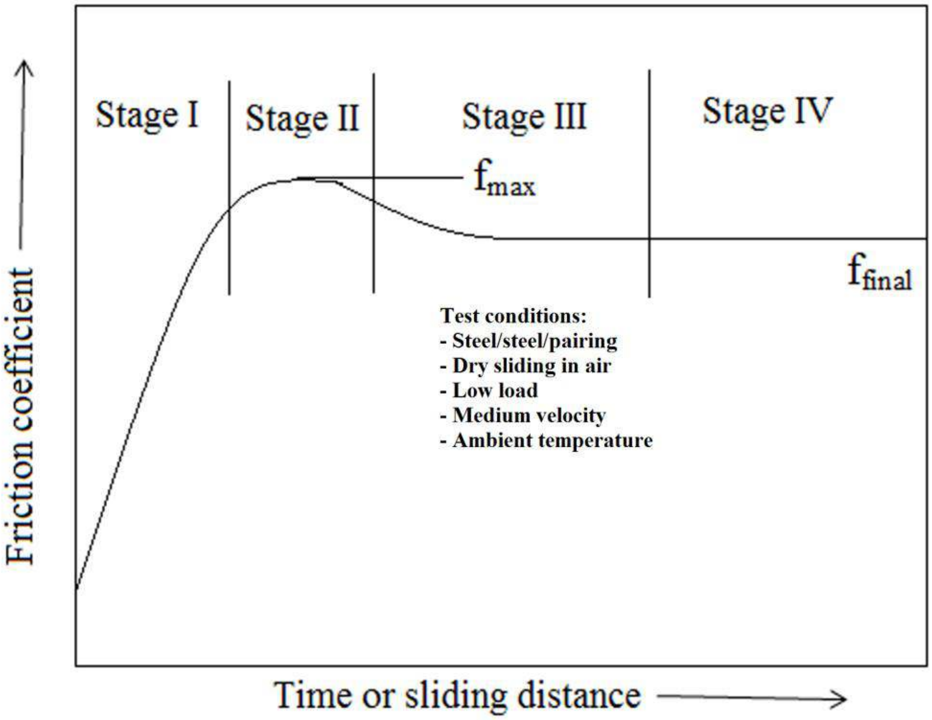

Figure 1.2 - Friction - time curve [Blau, 1992]

1.4 Factors Affecting Wear and Friction

Wear and friction depend on structural parameters like materials in contact, lubricants used, environment, microstructure, physical, mechanical and chemical properties of the materials used. Operating parameters like type of contact (sliding, rolling, reciprocating, and impact), applied load, velocity, temperature, and time duration also affect wear and friction both [Blau, 1992; Mohan and Mohan, 2015; Mohan et al., 2015].

1.5 Materials for Tribological Applications

Using appropriate technique, a material can be designed or tailored with combination of properties such as high specific strength, high hardness, high stiffness, high temperature strength, high wear resistance, good corrosion resistance required in chemical, aerospace, automobile and marine applications etc. Casting and forming techniques can be employed for achieving the desired properties for a specific need. However, the mechanical properties of cast products are not as good as that of wrought products, still the cast parts are widely used in various applications because it is a simple and cheap route to obtain particular combination of properties required for specific application. Among above mentioned properties, wear resistance is an important property which must be taken into account during selection and designing phase of materials. Wear loss takes place in almost all the components of a mechanical system like compressor piston, pump bodies, cylinder heads and blocks, crank cases, engine bearing and connecting rod bearing, clutch plate, and brakes. In selecting the materials for wear applications wear modes should be identified and chosen material should satisfy the requirements at all operating conditions. Materials in wide range are available for tribological applications which include ferrous and nonferrous metals and alloys, ceramics and cermets, solid lubricants and self-lubricated solids [Bhushan, 1999]

i. Ferrous Metals and Alloys

Cast iron and steels are most commonly available commercial alloys which are used in wide range of applications. Cast irons are basically iron-carbon-silicon alloys which contain 2 to 4% carbon and 1 to 3% silicon. Cast iron has good mechanical properties and excellent machinability and can be cast easily into complex shapes. Owing to above characteristics, cast iron is suitable for numerous applications. White cast iron containing carbon in combined form with iron as hard iron carbides provides good abrasion resistance. Presence of alloying elements in steels can significantly improve strength, hardenability, resistance to softening on heating to moderate temperature and refine the grains [Davis, 1994, 1995, 1996; Handbook, A. S. M., 1990a; Thelning, 1984]. Steels are widely used in areas where wear resistance and corrosion resistance properties are important. For determining the wear resistance of steels several factors like hardness, toughness, thermal treatments, and processing must be taken into consideration [Davis, 1994, 1995, 1996; Handbook, A. S. M., 1990a]. Low-alloy steels contain a small amount of alloying elements. Their properties can be tailored for a particular application by proper thermal treatments. These steels can be processed in many ways to make them suitable for tribological applications. Apart from these, bearing steels, tool steels and super alloys are also used in various applications requiring high wear resistance and high temperature strength [Magee, 1992; Maloney, 1992; Moyer, 1992].

ii. Nonferrous Metals and Alloys

The nonferrous metals and alloys have a wide range and can provide combination of properties aimed for particular application. But in many applications selection of a nonferrous metal and alloy depends on factors such as cost, availability of material, it’s shaping capability into a finished product, and tailoring its properties to meet the requirements for a particular application. Nonferrous metals and alloys include lead & tin base Babbitt’s, copper and aluminium which are used as linings in oil-lubricated bearings and other sliding applications [Booser, 1984; Bhusan and Gupta, 1991; Glaeser,1992; Hausner et al., 1970]. Among aluminium alloys, Al-Si is mostly used for tribological applications for manufacturing of many automobile components such as pistons, engine blocks, cylinder liner, roller type valve rocker and valve lifters [Mohan and Mohan, 2015; Pathak and Mohan, 1998; Shabel et al.,1992]. Other nonferrous metals such as Nickel, cobalt, molybdenum and alloys of cobalt and nickel are hard and can be used in high temperature applications. All these materials exhibit good wear resistance in corrosive environment [Handbook, A. S. M., 1990b].

iii. Ceramics and Cermets

Ceramic materials such as carbides, nitrides, borides, silicides and oxides of mostly refractory metals have high melting point. These are very hard and widely used as wear resistant materials in many tribological applications [Bhushan and Gupta, 1991; Davis, 1997; Glaeser, 1992; Haher and Smith, 1991; Lynch, 1981]. Cermets are the composite materials in which a metal or alloy is bonded with ceramics. Cemented carbide is most commonly used cermet which has high hardness and toughness, however, few other cermets such as cobalt bonded carbides, nickel bonded carbides and steel bonded carbides are also in use. Wear resistance of steel bonded carbides is somewhere in between tool steels and cemented carbides. The cemented carbides can retain their hardness even at temperatures where high speed steel becomes soft [Budinski, 1983; Handbook, A. S. M., 1990b].

iv. Solid lubricants

Solid lubricants are inorganic soft materials which have lubricating ability due to their typical lattice structure. These materials exhibit low friction and/or wear during sliding.

Molybdenum disulphide (MoS_2), graphite, and amorphous carbon are few solid lubricants which are used in many applications [Bhushan and Gupta, 1991; Bhushan, 1999; Braithwaite, 1967; Clauss, 1972]. Self-lubricating solids consists of polymer and polymer base composites which are mainly used for lubrication purpose at low loads, low sliding velocity and elevated temperatures [Bartenev and Lavrentev,1981; Bhushan and Gupta,1991; Brydson,1982; Fines and Bartolomucci, 1988; Harper,1975; Oleesky and Mohr,1964]. Most commonly used self-lubricating solids are graphite, MoS_2 and poly-tetra-fluoro-ethylene (PTFE).

With increasing demand for optimization of properties to meet future needs of light weight, energy efficiency etc., it has not been possible to cope-up with above materials. With composite materials the combination of properties can be achieved in a much better way.

1.6 Composites

It is difficult to achieve combination of properties in materials discussed earlier.Composite materials can be tailored to give range of properties as per the requirement. "Composite" can be defined as a material consisting of two or more phases (matrix phase and dispersed phase) which are chemically and/or physically different and separated by a distinct interface [Chawla, 2012]. Different constituents of composite materials are combined judiciously to achieve a material system which derives its distinguishing characteristics from the properties of its constituent phases, in terms of geometry, architecture, and properties of the interfaces. Composite materials have high strength and stiffness, along with low density when compared with matrix alloy, causing weight reduction in the finished product. The two main constituents of composite materials are reinforcement and matrix as discussed below:

- **Reinforcement**

Reinforcement is the discontinuous phase distributed in the matrix. The reinforcement material provides superior level of strength and stiffness to the composite. Mostly the reinforcements are harder, stiffer, and stronger than the matrix. Reinforcements are usually in the form of fibers or particles having different orientation and shape. A fibrous reinforcement is characterized by its aspect ratio (length/diameter ratio) which is an important parameter because the degree of load transfer from the matrix to the reinforcement is directly proportional to the aspect ratio of the reinforcement. Continuous fibers have preferred orientation and provide highest degree of load transfer which results in a significant amount of strengthening along the fiber direction. On the other hand discontinuous fibers have random orientation and exhibit lower strengths than their continuous fiber counterparts, but the properties of these composites are more isotropic in nature [Chawla, 2012; Vencle et al., 2004]. In addition, the cost of discontinuous fibers is also about one hundredth of the cost of continuous fibers reinforcement. There are mainly three types of discontinuous reinforcements viz whiskers, short fibers and particulates. Among them whisker reinforcement provides combination of strength and thermal stability. However, the faulted internal structures and irregular surface of whiskers could be a source of contamination [Ibrahim et al., 1991; Mortensen et al., 1988]. Further, relatively higher cost and limited isotropic properties have restricted popularity of whiskers as compared to particulate as reinforcement. The arrangement of the particles in composites can be either random or preferred, in the shape of sphere, cube or any other regular or irregular geometry.

Isotropic properties can be best achieved in particulate composites. Figure 1.3 shows different types of reinforcement used in composites.

- **Matrix**

Matrix is a continuous phase in composites and it binds the reinforcement together to keep it intact by virtue of its cohesive and adhesive characteristics. Metals, polymers or ceramic materials can be used as matrix materials in composites. Polymers have poor strength and stiffness, whereas, metals exhibit medium strength and stiffness with high ductility. Ceramic materials also have high strength and stiffness but they are highly brittle in nature. In case of polymer and metal matrix composites, the matrix provides a strong bond between reinforcement and matrix. Moreover, matrix also provides a solid form to the composite, which eases the handling during manufacturing. The matrix provides effective load transfer from matrix to the reinforcement and holds fiber reinforcement in the particular orientation so that the intended load is uniformly distributed throughout the composite. In case of ceramic matrix composites the main purpose of matrix is to increase toughness rather than the strength and stiffness.

1.6.1 Classification of Composites

Composites can be classified either on the basis of matrix or type of reinforcement.

1.6.1.1 Classification based on matrix type

According to matrix type, composites are classified as Polymer matrix composites (PMCs), Metal-matrix composites (MMCs) and Ceramic matrix composites (CMCs) which are discussed in the following sections.

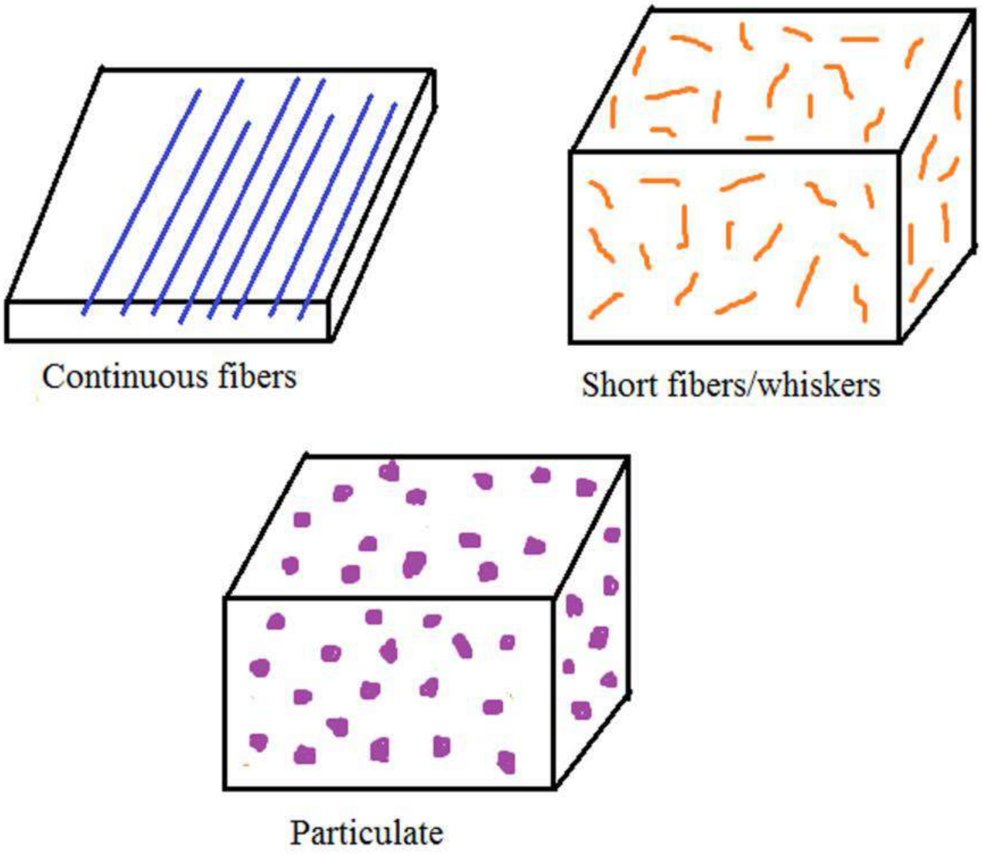

Figure 1.3 – Different types of reinforcements [Chawla, 2012]

➢ Polymer Matrix Composite

Polymer matrix composites (PMCs) are advanced composites which consist of polymer (e.g., epoxy, polyester, and urethane) reinforced with thin fibers of graphite, aramid or boron. These composites have very high strength as compared to conventional monolithic materials. For example, graphite/epoxy composite is almost five times stronger than steel. These composites are widely used due to their high strength, low cost, and simple fabrication technique.

The main problems in PMCs are moisture expansion and poor elastic properties in a particular direction [Mack, 1988]. Glass, Graphite, and Kevlar fibers are generally used in PMCs. Among these, glass is most commonly used due to its high strength, low cost, high chemical resistance, and good insulating properties. But it fails due to low modulus of elasticity, poor adhesion with polymer matrix, high specific gravity, sensitivity to abrasion (reduces tensile strength), and low fatigue strength. Graphite fiber composites are used in aerospace industries due to their high specific strength and modulus, high fatigue strength, and low coefficient of thermal expansion, but their application areas are limited due to their high cost, low impact resistance, and high electrical conductivity. Likewise, epoxy is costlier than other polymer matrices, and it is mostly used in aerospace industries [Schwartz, 1984].

- **Ceramic Matrix Composite**

Ceramic matrix composite have ceramic as matrix such as alumina, calcium alumino-silicate etc. which is reinforced with carbon fibers, silicon carbide etc. CMCs have high strength, high hardness, high service temperature limits, and low density. However, ceramics by themselves have low fracture toughness and fail catastrophically under tensile or impact loading. Fracture toughness of ceramics can be increased by reinforcing them with silicon carbide and carbon fibres. The combination of fibres and ceramic matrix makes CMCs attractive for applications requiring high mechanical properties and extreme service temperature, e.g. cutting tool, inserts (such as pins, bolts, screws, joints) etc. in oxidizing and high temperature environment [Chawla, 1998; Srivastava, 2006].

- **Metal-matrix composites**

Metal-matrix composites (MMCs) are generally composed of at least two physically and chemically different phases. Among these phases one phase is distributed in another one to provide properties not achievable with either of the individual phases. In MMCs, generally a metal or alloy is used as matrix phase in which a metallic or ceramic phase is dispersed as particles or fibres. Generally, aluminium, magnesium, titanium, copper or their alloys are used as matrix phase. Reinforcement phase can increase elastic stiffness and strength of metals, whereas, coefficient of thermal expansion and thermal & electric conductivities of metals can be reduced. MMCs have many advantages over monolithic materials such as high specific strength and high modulus with low density [Ashby, 1989; Buchanan, 1988; Kumar et al., 2011]. Aluminium and titanium can achieve low coefficients of thermal expansion if fibers of a material with low coefficient of thermal expansion such as graphite are reinforced while high temperature strength can be preserved. MMCs are more advantageous than polymer matrix composites due to their better elastic properties, higher service temperature, insensitivity to moisture, superior electric and thermal conductivities and also superior wear, and fatigue properties. However, some drawbacks of MMCs are also observed such as high processing temperatures and higher densities [Methews and Rawlings, 1999; Niskanen and Mohn, 1988]. Table 1.1 shows some applications of MMCs in automotive industries.

1.6.1.2 Classification based on reinforcement type

Composites are classified into two main groups based on reinforcement type. First one is fiber reinforced composite and the second one is particles reinforced composite. Fibre reinforced composites can further be classified as continuous and discontinuous fibre composites.

Table 1.1 - Potential automotive applications of Metal-Matrix Composites [Rohatgi, 1991]

System	Component	Properties required
Engine	Piston Crown, Valve	Good resistance to fatigue, creep, wear at High temperature
	Piston Ring Groove	Good wear resistance, weight reduction
	Rocker Arm	Weight reduction and high stiffness and wear resistance
	Wrist Pin	Good resistance to wear and creep with high specific stiffness,
	Cylinder Block (liner)	Good wear and seizure resistance, low friction, low weight
	Connecting Rod	Good specific stiffness and low weight
	Bearings	Low weight and reduced friction
Suspension	Struts	Good damping capacity with high stiffness
Driveline	Shift Forks	Good wear resistance with low weight
	Drive Shaft,	Good specific stiffness and fatigue resistance
	Gears, Wheels	Good wear resistance with low weight
Housings	Bearing and Pumps	Good wear resistance with low weight
Brakes	Disk Rotors Calipers	Good wear resistance with low weight

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➢ Fiber reinforced composites

These composites may have continuous or discontinuous fibres distributed throughout the matrix and commonly called as continuous fibres reinforced and discontinuous fibers reinforced composites respectively. Continuous fibers have high aspect ratio while discontinuous have low aspect ratio. Fibers are the principal load bearing constituents in these composites. The deformation of such composite along the fiber direction proceeds in the following four stages [Ibrahim et al., 1991], (i) elastic deformation takes place both in the fiber and the matrix, (ii) matrix deforms plastically while fibers continue to deform elastically, (iii) both fiber and the matrix deform plastically and (iv) fracture of the fibers and failure of the composite occurs.

The strength of the fibers reinforced composites is a function of aspect ratio, volume fraction, and orientation of the fibers. However, fibers spacing does not influence the strength. Although smaller diameter fibers have high strength but they are very costly. The strength of such composite varies linearly with volume fraction of the reinforcement. The high temperature strength of such composite depends mainly on the strength of the fibers [Srivastava, 2006].

- **Particle reinforced composites**

These composites generally contain equiaxed ceramic reinforcements. Only a limited amount of reinforcement can be reinforced in these composites due to processing difficulties and brittleness. The strength of such composite depends on inter-particle spacing, diameter and the volume fraction of the particles. The composite strength increases with increasing volume fraction of the particle and decreasing inter-particle spacing for a given diameter of the particles. Mechanical properties of particles reinforced composites are inferior as compared to continuous fiber reinforced composites. But, they are less expensive, than continuous fibre reinforced composites. Moreover, these composites are isotropic in nature [Ibrahim et al., 1991].

1.7 Aluminium Matrix Composites (AMCs)

Aluminium alloys are preferred over conventional tribological materials owing to their high specific strength and modulus, but limited wear and seizure resistance limit their use as tribo-materials [Chen and Alpas, 1996; Shercliff and Ashby, 1994]. Aluminium matrix composites (AMCs) have emerged as potential materials and replaced many conventional materials in many applications. Wide possible combination of excellent properties such as high wear resistance, low thermal expansion, and high strength to weight ratio etc. has put these materials in forefront [Alidokht, et al., 2011; Nami, et al., 2011; Rajan, et al., 2013; Sharifitabar, et al., 2011] and AMCs are considered as potential engineering materials for many tribological applications. Number of components such as brake drums/rotors, pistons,connecting rods, cylinder liners and blocks, gears, drive shafts, suspension components etc. have been manufactured by AMCs [Lloyd, 1994; Hassan, et al. 2009; Rao and Das, 2011]. Tribological properties of AMCs with different kind of reinforcements have been investigated by many workers [Baradeswaran and ElayaPerumal, 2013; Chaudhury, et al., 2005; Hosseini, et al., 2012; Jerome, et al, 2010; Kumar, et al., 2014; Niranjan and Lakshminarayanan, 2013; Rao and Das, 2011]. Table 1.2 lists selected reinforcements used in automotive components of Aluminium Matrix Composites and tensile properties of some selected cast AMCs at ambient temperature are given in Table 1.3.

1.7.1 Processing Techniques of AMCs

Processing techniques can be classified in two categories namely solid state and liquid state processing. Techniques are briefly discussed in the following subsections.

1.7.1.1 Solid state processing routes

Diffusion bonding is one of the most commonly used technique for joining the similar or dissimilar metals by inter-diffusion of atoms of two metallic contacting surfaces at elevated temperature. This can be employed for wide range of metal matrices with controlled fiber orientation and volume fraction. However, long processing time, high temperature and pressure are involved in the process which make it very expensive. Moreover, this technique is also not suitable for production of complex shape components [Chawla, 2012; Surappa, 2003].

Table 1.2 - Selected reinforcements used in automotive components of AMCs [Rohatgi, 1991]

Reinforcement	**Component**	**Property**	**Benefits**
SiC(p)	Piston	Wear resistance, high strength	Reduced weight
Al_2O_3 (f)*	Piston Ring Groove	Wear resistance	Higher running temperature
Al_2O_3 (f)*	Piston Crown (combustion bowl)	Fatigue resistance, creep	Opportunity to use Al, reduced reciprocating mass
SiC(p)	Brake Rotor, Caliper, Liner	Wear resistance	Reduced weight
Fiberfrax	Piston	Wear resistance, high strength	Reduced weight
SiC(p)	Drive Shaft	specific stiffness	Reduction of parts and weight
SiC(w)	Connecting Rod	Specific stiffness and strength; thermal expansion	Reduced reciprocating mass
Al_2O_3(f)**	Connecting Rod	Specific stiffness and strength; thermal expansion	Reduced reciprocating mass
Al_2O_3-SiO_2-C	Cylinder Liner	Wear resistance, expansion Gall resistance,	Increased life, reduced size
Gr(p)	Cylinder Liner, Pistons, Bearings	reduced wear and friction	Increased power output
TiC(p)	Piston, Connecting Rod	Wear, fatigue	Reduced weight and wear
Al_2O_3	Valve Spring. Retainer Cam, Lifter Body	Wear, strength	Reduced weight, increased life

Courtesy Springer-Verlag * Short fibers, ** Long fibers, p- particulate, w- whiskers

Powder blending and consolidation is a versatile technique for producing AMCs by blending the aluminium alloy powder to the ceramics (particles/short fibers/whiskers) which is followed by cold compaction, canning, degassing and high temperature consolidation process such as hot isostatic pressing (HIP) or extrusion. The matrix gets deformed significantly due to rigid particles or fibers. AMCs produced by this process contain thin oxide particles in the form of plate-like structure and act as a dispersion strengthening agent influencing the matrix properties during heat treatment [Surappa, 2003].

Table 1.3 - Ambient temperature tensile properties of selected cast AMCs

Matrix	**Reinforcement**	**Vol.% of reinforcement**	**Elastic modulus (GPa)**	**UTS (MPa)**	**Reference**
Al 2219	TiC(p)	15	69-117	400	[Rohatgi, 1991]
Al2014	Al_2O_3(p)	10-20	83-103	414-483	[Rohatgi, 1991]
Al6061	Al_2O_3(p)	10-20	83-103	241-345	[Rohatgi, 1991]
A356Al	SiC (p)	10-20	75-96	255-317	[Harrigan Jr. et al., 1991]
ADC12	Al_2O_3(f)	10	80	250	[Rohatgi, 1991]
ADC12	Carbon(f)	5	80	230	[Rohatgi, 1991]
F3N	SiC(p)	20	108	303	[Harrigan Jr. et al., 1991; Duralcan, 1999]
F3D	SiC(p)	20	114	352	[Harrigan Jr. et al., 1991; Duralcan, 1999]
A206	TiC(p)	20	96	400	[Harrigan Jr. et al., 1991]
F3K	SiC(p)	20	101	372	[Harrigan Jr. et al., 1991; Duralcan, 1999]
F3S	SiC(p)	20	99	359	[Harrigan Jr. et al., 1991; Duralcan, 1999]

p-particle, f- fiber,F3N-Al+10Si-1Fe-0.2Cu-0.65Mn-0.4Mg,F3D- Al+10Si-1Fe-3.25Cu-0.65Mn-0.4Mg-1.25Ni,ADC12- Al+ Si 9.6-12.0 Cu 1.5-3.5 Mg 0.3 max Zn 1.0 max Mn 0.5 max Fe 0.9 max Ni 0.5 max Sn 0.2 max, A206- Al+4.60 Cu-0.25 Mg-0.35Mg-0.22Ti-0.1Fe,F3K-Al+10Si-0.3Fe-3Cu-1Mg-1.25Ni-0.2Ti,F3S-Al+9Si-0.2Fe-0.2Cu-0.55Mg-0.2Ti

Physical Vapour Deposition (PVD) technique involves the deposition of a metal in the form of film coating by condensation of the vaporised metals on the desired surface. For the production of AMCs a high power electron beam is used for heating. This beam creates the vapour of desired material and this vapour is allowed to get condensed on the fiber surface. Composites with uniform distribution and high volume fraction (up to 80%) of fiber can be produced by this technique. PVD coatings have high temperature and good impact strength, and excellent abrasion resistance [Surappa, 2003].

1.7.1.2 Liquid state processing

Stir casting technique also known as vortex method is commonly used in production of AMCs. Flow chart of stir casting technique is shown in Fig.1.4. In this technique, the reinforcing phases are generally used in powder form. These powders, wrapped in aluminium foil, are charged into molten aluminium while mechanical stirring is continued in the melt. This process was initiated by S. Ray in 1968, when he introduced alumina particles into aluminium melt while stirring the melt [Ray, 1969]. This technique provides good distribution of the reinforcement material in the matrix alloy. Molten matrix material is stirred vigorously to form a vortex at the surface of the melt, and the reinforcement material is then introduced through the vortex. The stirring is continued till the melt is cast into the mould. During composite fabrication stirring helps in transferring particles into the liquid metal, and maintaining the particles in a state of suspension [Hashim, et al., 1999]. This technique is not suitable for the incorporation of submicron size ceramic particles or whiskers.

Another variant of stir casting technique is compo-casting in which the ceramic reinforcements are introduced into the alloy in semi-solid state. The reinforcements are likely either to float at the top or segregate near the bottom of the melt depending on their density difference from the melt. Therefore, a careful choice of casting techniques as well as of mould configuration must be made to obtain uniform distribution of reinforcement in compo casting of MMCs. Continuous stirring of the slurry in compo-casting leads to uniform distribution of reinforcement in the matrix and an intimate contact between reinforcement and matrix. The slurry viscosity can be reduced by increasing the shear rate and/or slurry temperature which provides good bonding among two phases even longer interaction of the phases can also provide good bonding of the phases. The main limitation of the technique is to fabricate composites with pure metals and eutectic alloys as matrix material. However, composites production having matrix of any alloy with wider semi-solid region, this technique is considered to be one of the prospective casting techniques [Hoskins, et al., 1982; Mehrabian et al., 1974; Rohatgi, 1991; Zhu, 1988].

Squeeze Casting or Infiltration processing is one of the oldest techniques used for casting the materials useful in the automotive industry. Flow chart of squeeze casting technique is shown in Fig.1.5. In this technique porous preforms of fiber or particulate reinforcements are prepared and then molten metal is infiltrated/injected under high pressure of about 100 MPa to fill all the pores and channels of the preforms. The short processing time involved for producing composites by this technique restricts the reaction between the reinforcement and molten metal to bare minimum. In these composites defects such as porosity and shrinkage cavities are not observed [Chawla, 2012; Luo et al., 1995b].

Liquid–solid phase change is very fast in this technique which results in non-equilibrium solidification and fine grain structure of composite is obtained. Besides good distribution and strong interfacial bonding, this technique also ensures smooth surface of the product. However, the process is very costly because it requires costly tools to withstand the high pressure and high temperature, and additional cost for tools maintenance also increases the product cost. Damaged tools can induce error in product dimensions [Kumar et al., 2015; Rohatgi and Asthana, 2001; Zhu, 1988]. Table 1.4 shows the comparison of cost involved in stir-casting, squeeze casting and powder metallurgy techniques.

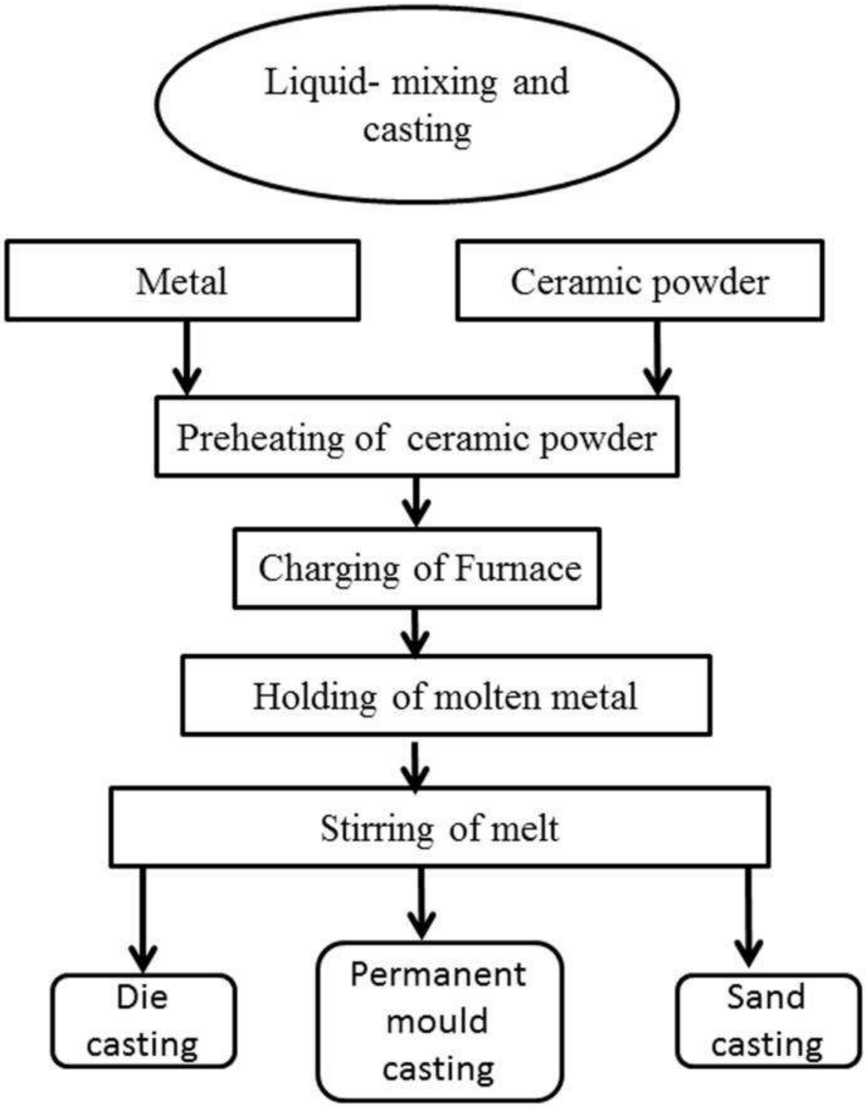

Figure 1.4 - Stir casting technique [Luo, 1995a; **Courtesy Springer-Verlag**]

Spray deposition involves atomizing of melt and allowing the droplets to solidify as powder and it is restricted to only metal powders. Semi-solid droplets are collected on a substrate. The process is fast and the transition from liquid to solid is very quick but slow cooling takes place in solid state after solidification. This results in refined grains, however, no significant increase in solute solubility is observed [Badia and Rohatgi, 1969; Srivastava, 2006]. AMCs produced by this process have inhomogeneous distribution of the ceramic particles, and strong interfacial bonding without any interfacial reaction. Porosity in the as-sprayed state is typically about 5% but secondary processing normally eliminates this. The cost of AMCs produced by this technique lies between stir casting and powder metallurgy process. Cost comparison of different processing methods and reinforcements is shown in Fig.1.6.

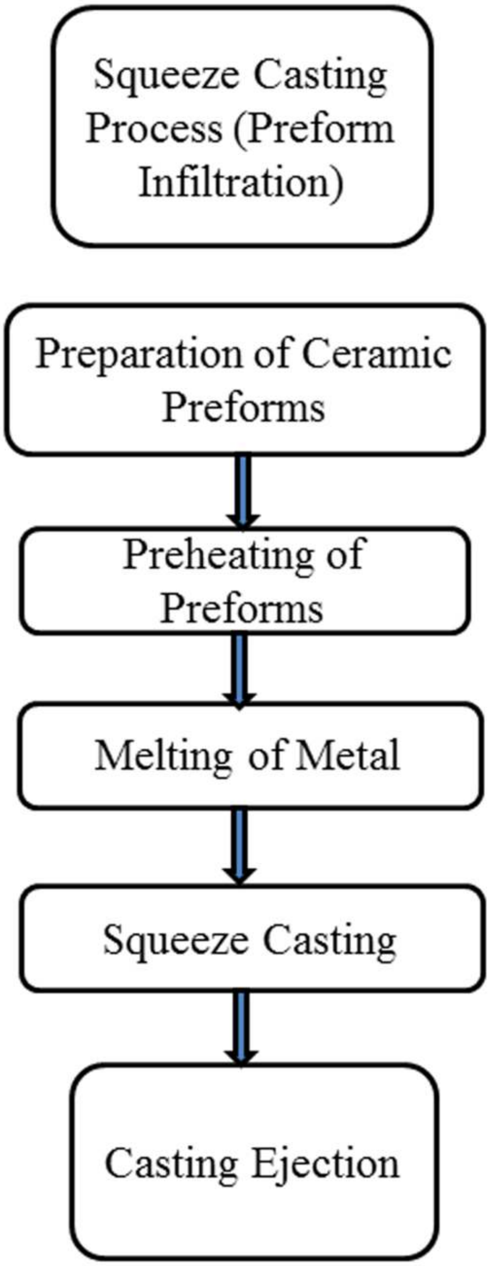

Figure 1.5 - Squeeze casting technique [Luo et al., 1995b; **Courtesy Springer-Verlag**]

Table 1.4 - Comparison of cost of stir casting, squeeze casting and powder metallurgy technique [Surappa, 1997; **Courtesy Elsevier Publication**]

Method	**Working range**	**Metal yield**	**Vol.% of reinforcement**	**Damage to reinforcement**	**Fabrication cost**
Stir casting	Wide range of shape, larger size (upto 500 Kg)	Very high >90 %	≈ 30	No damage	Least expensive
Squeeze casting	Limited by preform shape (up to 20 cm height)	Low	≈ 45	Severe damage	Moderately expensive
Powder metallurgy	Wide range, restricted size	High	-	Fracture	Expensive

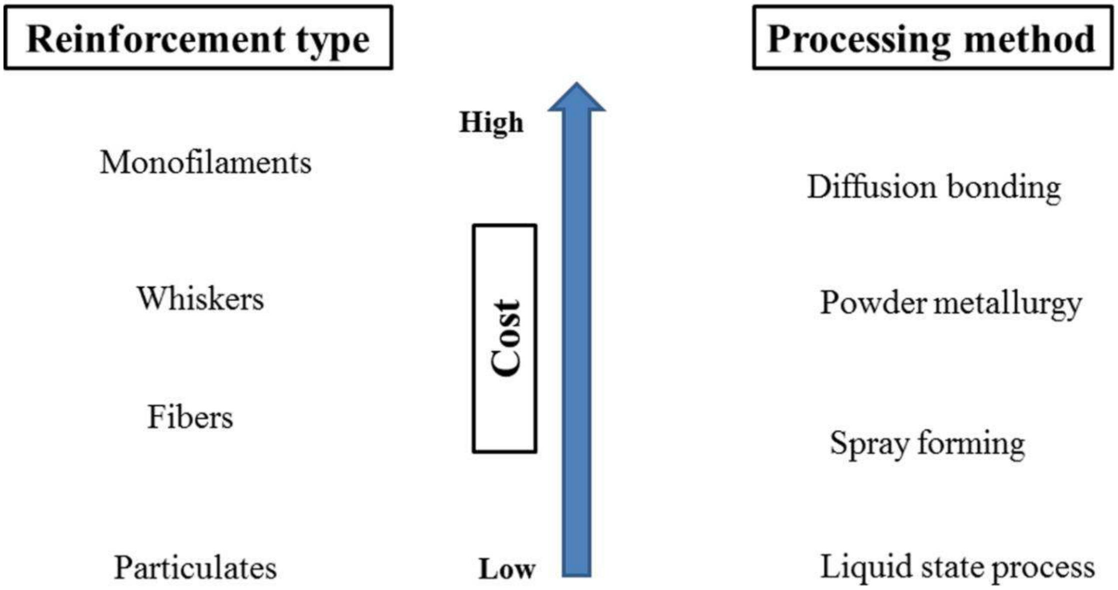

Figure 1.6 - Comparison cost [Lindroos and Talvitie, 1995]

Insitu Synthesis

AMCs can be prepared either by *exsitu* or *insitu* technique. In '*exsitu*' technique ceramic reinforcements are added externally to the molten metal, whereas, *insitu* technique involves the formation of reinforcement particles in the matrix itself by controlled metallurgical reactions. One of the final reaction products is the desirable reinforcement which is homogeneously distributed throughout the matrix. *Exsitu* techniques face problems of poor wettability, poor interfacial bonding and non-uniform distribution of reinforcement particles in the matrix. Generally *insitu* technique is preferred over *exsitu* because of many desirable attributes such as reinforcement are more coherent with the matrix, finer in size, clear interface between reinforcement & matrix, and more homogenous distribution of reinforcement in the matrix. In addition, the process is very simple and economical. However, the process needs to be monitored and controlled for reaction system [Hamid et al., 2006; Natrajan et al., 2009; Zhang et al., 2007].

In recent years, *insitu* technique for synthesis of aluminium matrix composites with different kind of ceramic reinforcement particles has been widely explored for preparing PAMCs.

1.7.2 Microstructure and Mechanical Properties

Work on variousAMCs is available and these AMCs have been produced by different *insitu* techniques using different matrices and reinforcements. Wang et al. [2010] prepared Al_2O_{3p}/Al composite by direct melt reaction and studied the microstructure and mechanical properties. The *insitu* formed Al_2O_3 particles were found in various irregular shapes and sizes ranging from 100 to 200 nm with uniform distribution. They also observed that composites had clean particle-matrix interface and strengthening was basically due to high dislocation density and grain refinement.

Jerome et al., [2010] and Liang et al., [2010] synthesized TiC in Al-4.5%Cu and aluminium respectively in different percentage and studied microstructure and tensile properties of *insitu* composites. Liang et al. [2010] observed spherical TiC particles in a size range of 2-3 µm. They also observed improvement in tensile properties due to the grain refinement and generation of high dislocation density. Jerome et al. also reported improvement in strength and hardness of the composites with increasing amount of TiC particles at the expense of ductility. Yang et al., [2014] fabricated 2024 aluminium alloy base composite with *insitu* formed AlN and reported tremendous improvement in mechanical properties after hot extrusion and heat treatment.

In past, metallic borides have been used extensively as reinforcement in aluminium or aluminium alloys. Lot of work is available especially on TiB_2 reinforced aluminium matrix composites fabricated through *insitu* technique. Microstructural examinations in various studies show that *insitu* formed TiB_2 particles are of hexagonal, spherical, equi-axed, cubic, and tetragonal shapes in the size range of 50 nm to 5 µm size [Benjamin and Volin, 1974; Chen et al., 2000a; Han et al., 2002; Kumar et al., 2008a; Kumar et al. 2015a; Lakshmi et al.,1998; Lu et al., 1997; Natarajan et al., 2009; Ramesh et al., 2010; Ramesh et al., 2011; Tjong et al., 2005; Usurelu et al., 2011; Xue et al., 2011; Yi et al., 2006b; Zhao et al., 2007; Zhang et al., 2007]. Mostly *insitu* composites have homogeneous distribution of second phase particles and clean interface between the matrix and second phase particles due to the absence of voids. Reaction products and *insitu* formed TiB_2 particles also prevent the oxidation of the surface of the particles within the matrix [Chen et al., 2000b; Kumar et al. 2015a; Lakshmi et al., 1998; Ramesh et al., 2010; 2011; Sivaprasad et al., 2008; Zhao et al., 2006; Zhao et al., 2007].

In general, hardness of Al-TiB_2 composites increases with increase in the amount of TiB_2 particles [Chen et al., 2000a; Kumar et al., 2008b; Kumar et al. 2015a; Mandal et al., 2009b; Rajan et al., 2013; Ramesh et al., 2011]. It is also reported that the ultimate tensile strength, yield strength, and elastic modulus also improve with increase in the volume fraction of TiB_2, but at the same time loss in ductility is also observed which is mainly due to the presence of Al_3Ti particles and porosity in cast composites [Chen et al., 2000a; Christy et al., 2010; Han et al., 2002; Kumar et al. 2015a; Lu et al., 1997; Tee et al., 1999a, 1999b]. This phenomenon has been observed by a number of workers for different matrices used [Christy et al.,2010; Gorsse et al., 2003; Kumar et al., 2007; Kumar et al., 2008a; Kumar et al. 2015a; Lu et al., 2001; Mandal et al., 2004; Ramesh et al., 2011; Smagorinski et al., 1998; Yi et al., 2006b; Zhao et al., 2006].

In most of the cases percentage elongation of the composites is adversely affected as the TiB_2 content increases, which is attributed to decreased pile-up spacing due to the increase in the TiB_2 percentage [Lu et al., 2001]. However, ductility of composites has been observed to improve with addition TiB_2 particles in some cases [Cheng et al., 1992; Han et al., 2002; Ramesh et al., 2011]. But the elastic modulus of composites improves when compared with base alloy due to the enhanced nucleation of TiB_2 particles in the base alloy matrix as has been observed by many workers [Christy et al.,2010; Gorsse et al., 2003; Kumar et al., 2008b; Kumar et al. 2015a; Lu et al., 2001; Ramesh et al., 2010; Tee et al., 1999a; Tjong and Tam, 2006].

Work on zirconium boride reinforced composites is very limited. Dinaharan et al., [2011] prepared AA6061/ZrB_2 composites with different weight percentage (i.e. 2.5, 5, 7.5 and 10) of ZrB_2 particles and studied the effect of ZrB_2 particles on microstructure and mechanical properties of composites. They observed that *insitu* formed ZrB_2 particles were within a range of 1 to 50 µm. Aluminium grains get refined with the dispersion of ZrB_2 particles that help to improve hardness and strength of composites but at the expense of ductility. Tianet al., [2014] prepared *insitu* AA2024/ZrB_2 nano-composites by direct melt reaction and reported formation of nano size ZrB_2 particles with refined aluminium grain morphology. They also reported improvement in tensile properties.

1.7.2.1 High temperature tensile properties

Several workers have studied different systems for high temperature applications to see the effect of temperature on strength retention due to reinforcement. Sahoo and Koczak, [1991] prepared Al-4.5wt.%Cu/TiC *insitu* composites and studied the tensile properties at elevated temperature. They observed that yield strength and tensile strength of composites were improved by 130% and 65% respectively when compared with Al-4.5 wt. % Cu matrix alloy processed in the similar conditions. They also observed that composite was able to retain its room temperature strength up to 250°C.

Hoseini and Meratian [2005] studied the tensile properties of *insitu* aluminium alumina composites at ambient as well as at high temperature. They observed that effect of alloying elements on strengthening was more significant at room temperature as compared to composite reinforced with 5 wt.% alumina particles. Whereas, at high temperature (300°C) tensile strength is largely controlled by reinforcement and composite has higher strength due to strain- hardening effect of alumina particles, while alloying elements lose their strengthening effect at high temperature.

Yiet al., [2006a] studied the high temperature mechanical properties of *insitu* TiB_{2p} reinforced Al-Si alloy composites and reported that tensile strength of composites were higher than Al-Si master alloy at temperatures ranging from 25° to 400°C. Recently, Han et al., [2015] also investigated the tensile behaviour and fracture mechanism of Al-12Si/4 wt. % TiB_2 composite in a temperature range of 25° to 350°C and observed the improvement in elastic modulus of composites as compared to matrix alloy. However, yield and tensile strength were higher at room temperature but both matrix alloy and composites exhibited similar strength above 200°C. The ductility of the composite was found to be lower than that of the unreinforced matrix alloy at 25° and 200°C, but no major difference was observed at 350°C. Morphology of the fractured surface of Al–Si /TiB_2 composite showed that at 25° and 200°C, the fracture mechanism was dominated by cracking of silicon particles and separated TiB_2 particles. Whereas de-bonding of the silicon particles coupled with failure of the interface between TiB_2 particles and matrix were the dominant fracture mechanisms at 350°C.

1.7.3 Ambient and High Temperature Tribological Properties

1.7.3.1 Ambient temperature tribological properties

Tyagi [2005] synthesized the Al-TiC composites reinforced with different volume fraction of TiC particles in commercially pure aluminium matrix by melt reaction method and performed dry sliding wear tests at different loads for a constant sliding velocity. The wear rate was observed to increase linearly with increase in load while wear rate showed a decreasing trend with increase in volume fraction of TiC particles. The average coefficient of friction decreased with increase in normal load as well as with increasing volume fraction of TiC particles. Shyu and Ho [2006] also observed same phenomena with *insitu* formed TiC particles in Al–5.1Cu–6.2Ti matrix.

Several researchers have dispersed metal borides in different aluminium/aluminium alloy matrices. Ramesh and Ahamed [2011] prepared *insitu* Al6063/TiB_2 composite and investigated friction and wear behaviour at different loads and sliding velocities. These composites exhibited lower wear rate and coefficient of friction as compared to unreinforced Al6063 alloy. Coefficient of friction of both i.e. base alloy and composites decreased with increase in load, whereas, COF increased with increase in sliding velocity. But wear rate of matrix alloy and composites increased both with increase in load and sliding velocity. Kumar et al., [2008a] also reported 50-60% decrease in wear rate in *insitu* formed Al-7Si/10TiB_2 composite as compared to Al-7Si unreinforced alloy. Mandal et al. [2009a] also studied effect of *insitu* formed TiB_2 in A356 aluminium alloy composites on dry sliding wear behaviour with load in the range of 19.6 to 78.4 N and 1 m/s sliding velocity. They observed significant reduction in wear rate with the addition of TiB_2 particles.They also reported that the effect of TiB_2 content is more pronounced on wear rate as compared to overall hardness of the composite. In another study on Al-4Cu/TiB_2 composites, Mandal et al. [2007] reported that TiB_2 particles improved the wear resistance and load bearing capacity of Al-4Cu alloy. Niranjan and Lakshminarayanan [2013] also observed same phenomena in Al-TiB_2 composites with uniform distribution of TiB_2 particles.

Kumar et al. [2010] prepared *insitu* AA6351/ZrB_2 composites with 3, 6 and 9 wt. % of ZrB_2 particles in a size range of 5-13 μm and studied the dry sliding wear behaviour at room temperature for as cast, solutionized and solutionized–aged composites. They observed that wear resistance of composites increased with increase in ZrB_2 content and it was maximum in aged composites after solutionizing. Dinaharan et al. [2012] studied the effect of *insitu* formed ZrB_2 in AA6061 matrix on dry sliding wear behaviour and developed a mathematical models to predict the effect of sliding distance, sliding velocity, mass fraction of ZrB_2 and applied load on wear rate. Maximum reduction of 39% in wear rate was observed for composite having 10 wt. % ZrB_2 particles as compared to base alloy. Zhu and Chen [2013] also studied the microstructural changes and dry sliding wear behaviour of A356/ZrB_2 composites. The composites were synthesized by magneto chemistry *insitu* technique using Al-K_2ZrF_6-KBF_4 system. They reported the reduction in wear rate of composites as compared to aluminium and reported that wear mechanism is changed from adhesive to abrasive with increase in ZrB_2 content.

1.7.3.2 High temperature tribological properties

Natrajan et al. [2009] studied high temperature sliding wear behaviour of Al6063/TiB_2 composites prepared by *insitu* reaction between molten alloy and salts (K_2TiF_6 and KBF_4). They observed that wear rate of composites increased with increase in applied load while it decreased with increase in TiB_2 weight percentage.

Kumar et al. [2009] studied the effect of load and temperature on dry sliding wear of Al-7Si/TiB_2 composites.They observed transition load from mild to severe wear for Al-7Si alloy as 80 N at 100°C, 60 N at 150°C and 40 N at 200°C. On reinforcing 5wt. %TiB_2 particles in the alloy, transition load increased from 40 N to 120 N at 200°C. When amount of TiB_2 was increased to 10 wt. %, transition load was observed to increase even at a high working temperature of 300°C. Jerome et al. [2010] studied the effect of TiC particles on high temperature wear resistance of composites at ambient, 120° and 200°C temperature. The wear rate of composites increased with increase in load, whereas, wear rate decreased with increase in weight percentage of TiC particles. They also observed that transfer layer formation mechanism dominated at room temperature, whereas, oxidative protective layer formation mechanism dominated at high temperature which leads to reduction in wear rate of composites.

Zhu et al. [2012] studied the dry sliding friction and wear characteristics of *insitu* (Al_3Zr+α-Al_2O_3)/Al composites at 100° and 200°C. At 100°C the wear rate of composites increased with increase in sliding velocity and attained a maximum value and then decreased with further increase in sliding velocity. However, wear rate decreased continuously with increasing sliding velocity at 200°C. Wear resistance of composites also improved with increase in volume fraction of reinforcement particles. Rajan et al. [2014] studied the effect of TiB_2 content and temperature on sliding wear properties of AA7075/TiB_2 composites. They observed improvement in wear resistance of AMCs with addition of TiB_2 particles, but with increase in temperature wear resistance decreased.

In view of the available literature it can be well understood that *insitu* technique is a potential technique to prepare particle reinforced aluminium matrix composites with variety of reinforcements such as Al_2O_3, TiC, AlN, TiB_2, ZrB_2 etc. and it has been widely explored specially to prepare the TiB_2 reinforced composites.Sufficient work is already available for mechanical and tribological properties of TiB_2 reinforced aluminium base composites at ambient as well as at high temperature but a very limited work is available on ZrB_2 reinforced aluminium matrix composites especially on high temperature mechanical and Tribological studies. Among various ceramic reinforcements zirconium di-boride (ZrB_2) is an outstanding reinforcement to develop AMCs due to its high melting point, high hardness, good chemical inertness, superior high temperature strength, high wear resistance, and better thermal and electrical conductivity [Zhang et al., 2008, 2009].

Hence, in the present investigation *insitu* technique has been used to reinforce different vol. % of ZrB_2 particles in AA5052 aluminium alloy to widen its application area for tribological applications. AA5052 is an aluminium-magnesium alloy with medium strength, good formability, good weldability and good corrosion resistance, hence, it has been chosen as matrix alloy. Presence of magnesium in aluminium gives rise to strength without losing ductility. It also acts as a surface active element and reduces the interfacial energy which results in enhanced wettability and uniform distribution of reinforcement [Fan et al., 2005; Jha and Dometakis, 1997].

1.8 Objectives of the Present Study

Objective of the present study is to develop alternative material for automotive applications with improved mechanical and tribological properties.

The following steps are followed to achieve the goal,

- Synthesis of AA5052/ZrB_2 composite with different vol. % of ZrB_2 particles by *insitu* reaction technique.
- Study of microstructural properties to critically analyse the ZrB_2 reinforcement particle morphology, size, distribution and interfacial characteristics between aluminium matrix and ZrB_2 particles.

- Study the effect of ZrB_2 particles on mechanical properties of AA5052/ZrB_2 composites at ambient temperature.
- Study the effect of different operating parameters such as sliding distance, applied load, and sliding velocity on wear and friction characteristics of AA5052/ZrB_2 composites at ambient temperature under dry sliding conditions.
- Study the tensile properties of AA5052/ZrB_2 composites at high temperature.
- Study the effect of different parameters such as applied load, temperature and vol. % of ZrB_2 particles on dry sliding wear and friction characteristics of AA5052/ZrB_2 composites at high temperature for a fixed sliding distance and sliding velocity.
- Study of worn surfaces and wear debris under SEM, EDS and profilometer to understand the various wear mechanisms involved during the wear process.